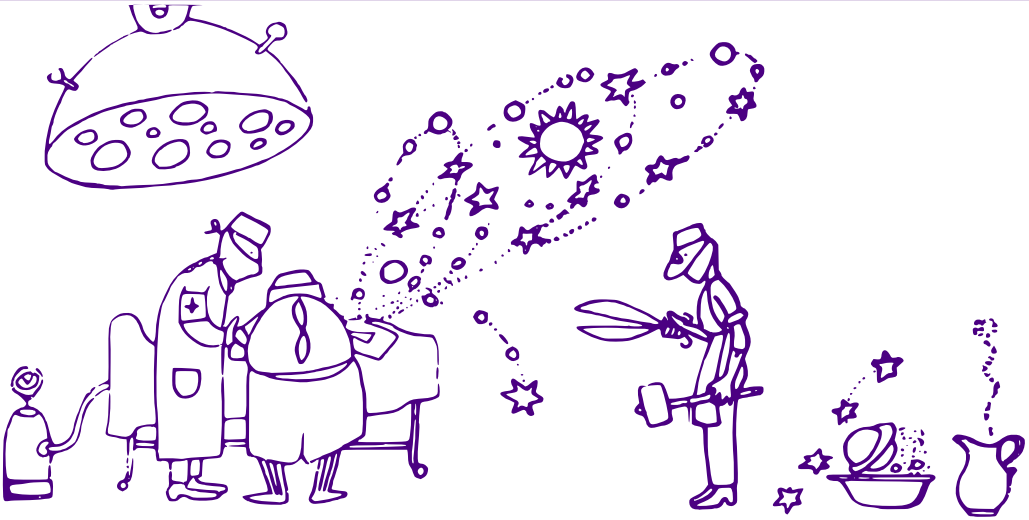
Eureka

Engaging Essays in Cosmology

Anatoli Tomilin



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Eureka

Engaging Essays in Cosmology

ANATOLY NIKOLAEVICH TOMILIN

A. Tomilin is a lecturer at an institute. **Engaging Essays on Cosmology** is not the first book by this author.

Young readers have repeatedly encountered his name in the pages of journals and popular science collections. Several works have come from his pen, published by the "Children's Literature" publishing house, including the booklet **For What – Nothing**, written in collaboration with N.V. Terebinskaya, the book **Project Alpha K-2**, as well as the book **Engaging Essays on Astronomy**, issued by "Molodaya Gvardiya."

This English translation of the book in English by Damitr Mazanav, has an extended epilogue containing exciting new discoveries the theories from 1970s to 2026 that have fundamentally changed our views about Universe.

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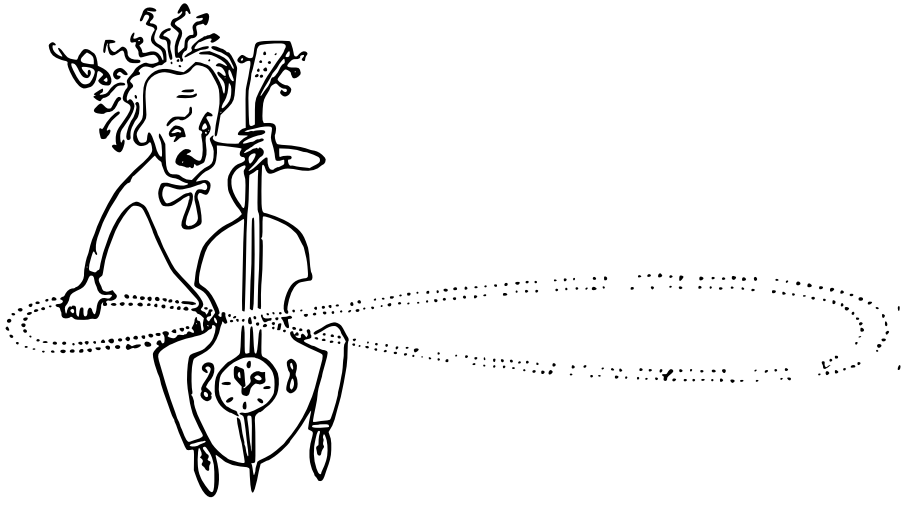

Engaging Essays in Cosmology

Anatoli Tomilin

Translated from the Russian by
Damitr Mazanav

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Anatoli Nikolaevich Tomilin
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Translated from the Russian & typeset in LaTeX by *Damitr Mazanav*

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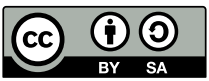

Annotation

A book of essays and short stories in three parts and ten chapters about the people and the achievements of the great science of the structure and development of the Universe from antiquity to the present day, composed and written on the basis of many sources by the author.

Translator's Note

> Of all the sciences, cosmology paints the biggest picture with the thinnest paint.
>
> William R. Corliss

This is the fourth book I am translating the *Eureka* series. The author A.N. Tomilin has written several popular science books. We have earlier seen his book on cosmogony, titled *Fascinating Cosmogony*. This book is on a related theme of Cosmology. I was first introduced to ideas of cosmology and general relativity during my masters. Since

then, the idea that we can infact study and make sense of the origins and structure of the universe at the largest scale have fascinated me. Translating this book in many ways was refreshing some of the ideas of cosmology and general relativity that I had learned. The quote by Corliss is indicative of how with limited data, we here on Earth, an insignificant part of the universe can make sense of it at all, constructing theories that will make sense of what we observe.

Since the book was written in 1971, several speculative hypotheses presented in the book have not been supported by data. To indicate this, at some places I have added sidenotes with my initials "DM". I have also added an **Epilogue: Cosmology as of 2026** which summarises some of the major landmarks in the themes discussed since the book was written in 1970s. Another change that I have added is to give the chapters descriptive titles. Originally, the chapters were just numbered, but I thought giving descriptive titles would be a better choice.

The reader will occasionally encounter brief, aphoristic remarks attributed to Kozma Prutkov in the last chapter. These are not incidental embellishments, but deliberate inclusions. Kozma Prutkov was not a single individual, but a fictional author created in nineteenth-century Russia by a group of writers, including Aleksey Tolstoy and the Zhemchuzhnikov brothers. Presented as a pompous yet self-assured thinker, Prutkov's writings consist of concise maxims, paradoxes, and satirical observations on knowledge, reason, and human pretension.

At first glance, such a figure may seem out of place in a discussion of cosmology. Yet the inclusion is not without purpose. Scientific inquiry, particularly in a field as vast and abstract as cosmology, carries with it a natural tendency towards overconfidence in models, measurements, and interpretations. Prutkov's aphorisms serve as a quiet counterpoint to this tendency. They remind us — often with a touch of irony — that clarity is hard-won, that appearances can mislead, and that systems of thought, however elegant, may conceal their own limitations.

There is also a more practical reason. Cosmology deals with scales and concepts far removed from everyday experience. At such distances, both literal and intellectual, language can easily become either overly technical or excessively grand. A well-placed aphorism has the virtue of restoring proportion. It compresses an idea into a form that can be held in mind, even as the surrounding discussion expands beyond immediate intuition.

The remarks of Kozma Prutkov are therefore included not as commentary on specific results, but as companions to them. They are meant to be read not as authorities, but as provocations — brief interruptions that invite the reader to pause, reflect, and occasionally question the very framework within which the narrative unfolds. Mistakes and omissions (and I am sure they will be there), if any, are my own.

Damitr Mazanav
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Instead Of An Introduction

> — an address in which the author, using every argument available to him, attempts to persuade the reader not to take up this book
>
> The Author

Dear Reader,

Before you lies a book about *cosmology*. But before we come to the substance of the matter, let us agree on what we both understand by this term.

Cosmos — from Greek — means "Universe."
Logos — in the same ancient language — means "concept, doctrine, or science."

Putting the two parts together, we can at once put an end to semantic investigations and obtain:

Cosmology — the science that studies the Universe. Short and simple.

One small detail remains unclear — what are we to understand by the word "Universe"? There is a somewhat light-minded definition which states: "The Universe is everything that exists around us." So people used to say. And so we sometimes repeat, without reflecting on the range of the reality that surrounds us.

And that range is rather vast. It stretches from the living to the lifeless, from human relationships to the collision of elementary particles and galaxies. From mesons with a "lifetime" of billionths of a second to stars whose age is counted in billions of years. From photons with zero rest mass to quasars — gigantic clusters of raging matter that have gathered within themselves the mass of billions of suns ...

The definition "everything that exists" turns out to be rather vague. Is anyone truly capable of grasping absolutely everything? Nor is there any need to strive for such a thing. Wise people say that to study everything means to study nothing. It is no accident that science has been divided into separate little plots, each carefully tended by its vigilant

owners.

We mentioned elementary particles — and see how the physicists frown. The mysteries of matter at its most elementary stage are the prerogative of particle physics.

We referred to quasars and galaxies — and the astronomers and radio astronomers grow alert. Both groups dislike being confused with one another, yet if the interests of the muse Urania are threatened, they enter the fray together.

We touched upon the probability of particle collisions and the calculation of the forces of interaction between enormous galaxies — and the mathematicians merely raise their eyebrows in surprise. These cultivated people are deeply convinced that any science which has not yet become a branch of mathematics is akin to charlatanism. Convinced — yet, out of politeness, they remain silent.

And yet, despite the protests of physicists, the stern faces of astronomers, and the raised eyebrows of refined mathematicians, all three sciences enter as equal ingredients into the common cauldron of cosmology. And not only they. There is yet another ...

Look around you: everything that surrounds us has its beginning, and everything that surrounds us has its end. So common sense tells us; so too does the very finiteness of our own existence in this world. You were born, dear reader, and came into a world in which you had never before existed. Many years will pass — perhaps very many, a whole lifetime — and you will leave the world forever,

while it will remain just as beautiful ...

"Never" and "forever" — these words carry the chill of the kingdom of Hades. But do such notions truly exist? We are materialists. We know that even humanity on our planet, even life itself upon it, is not eternal. If we are to believe the scientists, life arose not so very long ago. It developed from a lump of protoplasm into a clever, though not especially attractive, hairy ape, which later became a human being. Yet a time will come when first people, and then life altogether, will leave the Earth. Our planet will become unfit for the "mode of existence of protein bodies..."

And the planet itself is not eternal. The Sun is not eternal. The stars are not eternal, nor the galaxies — perhaps not even the Universe ...

Have you ever thought about this? Have you tried to look behind the façade of such words as "always" and "never," "eternity" and "infinity," if only to glimpse the abysses they conceal? For if the Universe was born and will die, then what existed before the birth of the very first, the very, very first star? And what will come afterwards? ...

"Oh, come now ..." a sensible reader will say politely. "Philosophy!" And he will be right. Philosophy! Precisely philosophy is the fourth ingredient that enters into the science of the Universe. Physics, mathematics, astronomy, and philosophy seated at the round cosmological table. The author very much wishes to emphasise the word "round," for not so long ago cosmology was readily

described as a part of "astronomy." And now? Now cosmology is the science of the Universe as a whole. So it is written in the astronomy textbook. Do you feel the difference? A science ...

The encyclopaedia refines the definition:

> "Cosmology is the doctrine of the Universe as a whole, including the theory of the entire region accessible to astronomical observation as part of the Universe."

After this, the concept of cosmology acquires, in the astronomical sense, a global character and requires further explanation: *what does cosmology study, and upon what does it rest?*

Let us refer to the opinion of the well-known Soviet specialist A.L. Zelmanov:

> "Modern cosmology considers the distribution, interaction, and motion of masses in world space, its geometrical properties, and the transformations of energy in the Universe."

That, indeed, is already an answer. And now as to its foundations:

> "It (cosmology) relies upon empirical information about the structure, properties, and behaviour of the observable part of the Universe, upon the fundamental laws of physics, and, in the far-reaching generalisations characteristic of cosmology, also upon general philosophical considerations."

That too is clear: observations plus theory plus philosophi-

cal generalisations.

And finally, in order to conclude this first meeting with cosmology and to assess its place in the modern world, it is appropriate to quote the words of Academician Vitaly Ginzburg, who stated that "in the science of inanimate nature there now exist only two fundamental problems: the physics of elementary particles and cosmology."

Now, perhaps, the author may feel at ease. A thoughtful reader, having read all these definitions, should come to the conclusion that cosmology is a purely theoretical, "pure" science, possessing no particular practical significance. What, then, is it needed for? Merely to think? To burden one's mind with accursed questions to which the priests of Zoroaster and Buddha gave far more intelligible answers, from the point of view of "common sense," than we are able to give today?

Lamenting the lost golden age, the wise Erasmus of

Rotterdam wrote:

> "... the people of old were too God-fearing to probe with impious curiosity into the secrets of nature, to attempt to penetrate the hidden causes of things; they would have regarded it as sacrilege for a mortal to desire to become wiser than his allotted fate permitted."

As yet, comparatively few popular books have been written about cosmology. First, because for quite a long time it was indeed one of the branches of astronomy, and by no means the most accessible. Second, and the author states this with full responsibility, neither theoretical physics, nor the geometry of multi-dimensional spaces, nor, still less, general relativity together with the philosophers' disputes about infinity and the problems of time, are gifts easily suited to popular exposition.

All this compels the author to ask the discerning reader to regard his book as a story of the adventures and misadventures of ideas and of their creators, making no claim to particular scientific strictness.

The beginning of the road towards the modern "cosmological model of the universe" is strewn with ashes. The pages of books burned at the stake have mingled with the ashes of their authors.

Today there are too many cosmological hypotheses for them to fit upon a single pedestal of truth. Moreover, they are irreconcilable, intolerant of one another, each claiming to provide the only correct description of the universe.

Nor can different ideas coexist peacefully. For we have but one universe, "published", as the French mathematician Henri Poincaré once said, "in only one copy".

Yet does this mean that, if to this day there is no reliable and sufficiently comprehensive theory of the universe, there is no point in speaking of this science at all? In an age saturated with information, such a conclusion may seem tempting — but it is primitive.

Curiously, in history there has not been a single truly great figure of science, not a genuinely authentic scholar, who did not devote at least part of his work to constructing a picture of the universe. Why, then, is this picture so important to us? And why has it always been important to humanity?

The author trusts that, having read the book, the reader will answer these questions for himself.

The author is deeply convinced that, had there been no Pythagoras and Democritus, no Aristotle with Ptolemy, we could not count among our achievements such names as Nicolaus Copernicus, Isaac Newton, Mikhail Lomonosov, Albert Einstein and Alexander Friedmann.

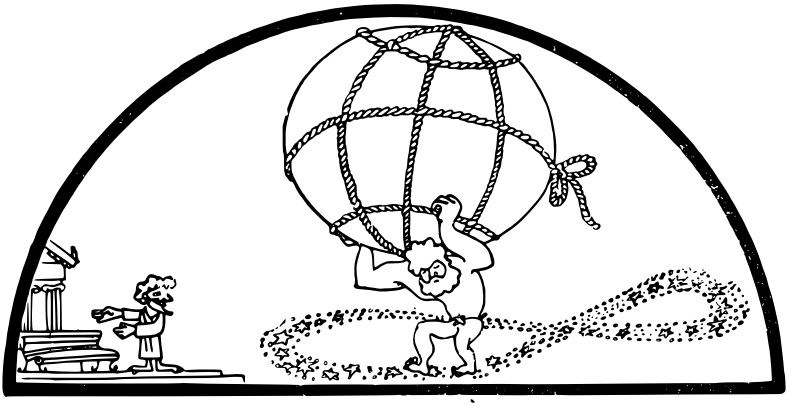
Every idea, even if it may seem naïve from the standpoint of the twentieth century, provided it was born in suffering and in the search for truth, is our greatest and most essential treasure. From this perspective, the idea of Thales of Miletus — who merely refused to invoke the gods in explaining natural phenomena — is no less worthy

of respect than the solution by Alexander Friedmann of Albert Einstein's cosmological equations, or the proclamation of the principle of the expanding universe by the astronomers Edwin Hubble and Georges Lemaître.

For this reason, before turning to the hypotheses and theories of our own day, the author invites the resolute and courageous reader on a long journey into the depths of time, along certain milestones in the history of science. And if such a voyage does not alarm you — then let us be on our way.

Part I.

People



1. The Miletus Manifesto

In which the author relates how well the universe used to be arranged, and urges the reader not to neglect the wise counsel of the well-known "thinker" Kozma Prutkov concerning the immeasurability of the immeasurable.

Once, when night had covered the heavens with her invisible mantle, the celebrated French philosopher René Descartes, seated upon the steps of his household staircase and gazing with the greatest attention at the sombre

horizon, was approached by a certain passer-by with the question:

> "Tell me, sage, how many stars are there in this sky?"
> "Scoundrel!' he replied. "No one can embrace the immeasurable!"

These words, uttered with the utmost fervour, produced upon the passer-by the desired effect.

Thus wrote "Retired Premier-Major and Knight Fedot Kuzmichev, son of Prutkov." His grandson, Kozma Prutkov actual State Councillor and Director of the Assay Office was more laconic.

Strictly speaking, the book might well have ended here. And yet... it is interesting to learn how such a categorical opinion about the immeasurable arose. And is it truly as correct as it is resolute?

1.1 When the Earth Was Flat...

At first everything was simple. The question of the structure of the universe did not particularly concern anyone, except the authors of myths and legends. People lived calmly and happily. When they were hungry, they went hunting. Having eaten their fill, the tribe slept. A person's entire world was limited to the area occupied by the hunting grounds.

Thousands upon thousands of years have passed since then. Humanity has progressed, and not only in quanti-

tative terms. True, here and there guardians of tradition remain those for whom the chief concern in life is still simply "to obtain." Their horizon, naturally, is even today confined to the sphere of their "hunting grounds".

But this book is not for them. It is for the reader who, by the very fact of taking an interest in so remote a subject, has already laid claim to the title of thinker.

It is sometimes said in jest that a person begins to think out of sleeplessness. And who knows whether, in the mind of some forefather of ours, worn out by insomnia, there first arose the thought:

> "What, in fact, is the world into which a human being comes? The world in which he lives and which he leaves with such reluctance and difficulty?"

A troublesome thought! Harmful, if only because it finally drives away healthy sleep, even after a hearty meal. Doubts then appear; the blissful feeling of self-satisfaction vanishes... In short, with the coming of reflection — farewell to a happy life. Anxiety takes possession of man.

What, do you prefer an anxious existence? Then you too, reader, belong to those who, having given birth to doubt, created science and thereby released the genie from the bottle. It was someone of your company who once began to ponder what the surrounding universe is. He merely began to think — and ever since we have been unable to stop.

The earliest ideas about the universe were, naturally, connected with direct observation, with everyday experi-

ence, with common sense. And common sense said: look about you, go to the left, go to the right — everywhere you go, the Earth lies before you. There are mountains upon it, there are rivers. But the Earth itself is flat, like a palm, like a pancake, although no one has seen its edge or end. At this point reflection ceased. A flat Earth one could imagine. But its boundlessness?...

Before the first circumnavigation by Ferdinand Magellan, the voyages of merchants were radial in character, like tourist routes for beginners. Having reached their final point, ships would turn back, leaving astern the terra incognita and their unsatisfied curiosity. (Let us add, for completeness, that *terra incognita* means in Latin "unknown land".) The shorter the route and the calmer the voyage, the more dreadful were the tales and the more inspired the falsehoods upon return — a naïve device, yet one capable of discouraging potential rivals in the discovery of distant lands.

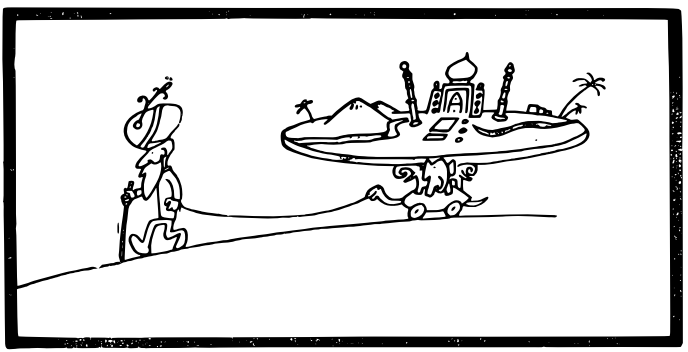
Yet, despite their championship in the art of exaggeration, it was precisely the seafarers who first noticed how the masts of a pirate ship gradually disappeared beyond the horizon... Gradually! Was it not this observation that led the ancient Babylonians to imagine the Earth as the curved arch of a gigantic bridge? And the Indians to picture it as a semicircular crust protruding sideways from the boundless ocean?

The ocean limited the Earth, but did not free the mind from thoughts of infinity. Of course, the boundlessness of

watery expanses was easier to accommodate in the imagination than the endlessness of land. But if our planet is surrounded by water, why has it not sunk? A stone sinks, a lump of clay sinks! Perhaps the Earth, in the form of an island, descended infinitely downward? But then one must suppose that the World Ocean has a bottom — and therefore shores as well...

This gave rise to new difficulties. Indian Brahmins tried to prop up the Earth with pillars, with the backs of elephants, making the latter tread upon the shell of a gigantic tortoise. And the tortoise was set to swim in the boundless ocean...

Once again the mind encountered the incomprehensible notion of infinite space — encountered it, and found itself at a dead end.



The matter was no better with time. Had the world existed for ever, or had it once been created by someone?

On the one hand, as far back as a person could remember, the surrounding nature had always been as he saw it at that very moment — save that the elderly of every age were convinced that in their youth the sun had shone more brightly, the weather had been finer, and the young more courteous and respectful.

On the other hand, everything a person saw around him had its beginning and its end: living beings were born, hatched from eggs; mountains and rivers arose from the violence of the elements — earthquakes, volcanic eruptions, and the like. Why, then, could not the whole Earth once have arisen in the same way?

Here the author hastens to remind us that the concept of "the Earth" for a very long time replaced for people the concept of "the whole world." Had our ancestors solved the problem of the Earth's origin, they would quite readily have extended the discovered principle to the universe. But if one assumes that the Earth was once born, questions immediately follow: who assisted in this, how and when did it happen, and what was there before? At the same time, somewhere in the distance, there loomed the rather alarming thought that everything which has a beginning must also have an end.

Any thought, when confronted with the absence or insufficiency of facts, is compelled to turn to imagination.

In short, the reader sees for himself that it might have been better not to begin thinking at all. Then everything would have remained simple... But if we paraphrase Aris-

totle, who said that "nature abhors a vacuum," we might frame a neat aphorism to the effect that the "human mind abhors the unknown". Filling the void of ignorance, people themselves create the missing links in the picture of the world with the aid of fantasy and myth, and, reflecting reality in their consciousness, fashion a spiritual image of their material surroundings.

The sources of even the most ancient and intricate myths may be found in everyday life — just as, in the form of a fabulous dragon, one may easily discern separate features borrowed from the most peaceful creatures that once surrounded humankind.

> "...Tiki sailed in his canoe and, to amuse himself, went fishing. Once, lowering his line deeper than usual, he felt that something large had taken the bait. Straining, he drew to the surface of the ocean the island of Nukagiva. The god enjoyed such fishing. He cast his line in other places and soon brought to the surface all the islands on which the Kanakas live."

This is a very ancient tale. The author has never visited the Marquesas Islands, never sat beneath rustling palms nor listened to the unhurried conversation of the waves. Yet he would wager that even today, as a thousand years ago, Polynesian grandmothers tell their Polynesian grandchildren this marvellous legend of how the god Tiki created the world. Oral folklore is, as a rule, more enduring than printed books.

The content of the myth presents one of the most primitive cosmological hypotheses. The god creates the world

by a method familiar from early childhood to every islander — fishing. Is this not a reflection of reality? And each people has its own reflection.

Consider, for example, a myth of the peoples of Mesopotamia in the time of Assyrian rule. Century after century, endless wars raged upon the poor soil between the rivers. The supreme Assyrian king cruelly suppressed the uprisings of conquered peoples.

> "In those times when what was above had not yet been called heaven, and what was below had not yet been called Earth, Apsu, the boundless abyss, and Mummu Tiamat, the chaos of the sea, united and brought forth fantastic beings: warriors with the bodies of desert birds, men with the faces of ravens, a bull with a human head, a dog with four bodies and the tail of a fish. Then lesser gods were born. But Tiamat, seeing her dominion steadily diminished by the younger gods, sent against them hordes of monsters.
>
> Yet Marduk, chosen by his equals as their leader, challenged Tiamat to single combat. He attacked her with storm and tempest, ensnared her in a net, pierced her with his spear, and cut her in pieces. He split her in two like a dried fish, placing one half high above to form the heavens, and casting the other beneath his feet to create the Earth. He fixed the stars in their final places, marked out the paths of the Sun, Moon and planets, created the year, the month and the days. After this, he ordered his father Ea to cut off his head, so that man might be born alive from his blood, mixed with clay."

Naturally, after this operation Marduk himself remained alive and unharmed. Marduk was a god. The gods were immortal. And immortality once again led to infinity.

Infinity in space, infinity in time — this was perhaps too heavy a burden for the minds of people in those days. Infinity jarred with every myth, not least because it deprived the gods of their principal occupation: the "creation of the world." To find peace, humanity had, in the end, to rid itself either of the idea of God — or of infinity.

1.2 In the Homeland of Science

Science is one of the forms of social consciousness — so we say today. Its principal task is to provide humanity with an objective picture of a world independent of supernatural forces; to acquaint us with the laws governing its development and to teach us how to make use of those laws. True, under conditions in which antagonistic classes and states exist, the solution of the latter task may lead to dangerous consequences. Examples have already occurred: Hiroshima — 1945. And yet ahead lie the harnessing of stellar energy, psychophysical influence at a distance, and control of the genetic code...

For this reason, science must concern itself not only with the accumulation of natural knowledge, but also with ensuring the reasonable — that is, rational and responsible — use of the laws it discovers, caring for the progress of

society no less than for knowledge itself.

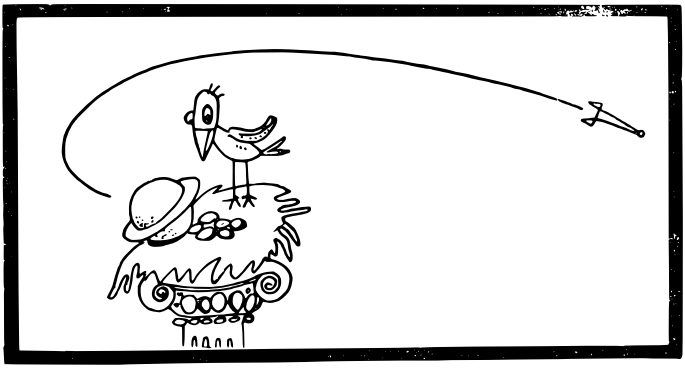
All these are thoughts of our own day. But there was a time when science, in the sense with which we began this section, did not exist at all. Of course, people possessed a certain stock of practical knowledge, skills and signs. Yet their understanding of the causes of observed phenomena was exceedingly weak. "It is God's will! God gives, God takes away!" — an exceptionally convenient formula for justifying ignorance, capable of explaining everything and placing an insurmountable barrier in the path of inquiry. To create science, it was necessary to sacrifice the gods.

It is generally held that science was born in Ionia, a colony of ancient Greece in Asia Minor, around the seventh century before our era. At that time the largest city along the entire Asia Minor coast was Miletus, a city-state, or polis. Such a form of political organisation was widespread in ancient Greece. Even today some Western European philosophers regard it as an ideal form of social order. They dream of a return to a golden age, forgetting that history never repeats itself in the same form.

So that the reader may harbour no illusions about the absurdity of such ideas, the author will briefly recall the principal features of the organisation of the city-states, or poleis.

They usually consisted of the city itself and a small adjoining territory. To enjoy full civic rights, a citizen had to satisfy three conditions: he had to be a man, to own land, and to possess slaves. Only then could he take part in the

popular assembly and in the political life of the polis — a life that was often turbulent.



Because of the low productivity of slave labour, the cities constantly suffered from a shortage of manpower. Time and again, in the central squares of the city-states, amid the cries of heralds and the roar of the crowd, civic militias were assembled and sent to wage war upon their neighbours. The principal spoils of these wars were slaves. "The city-states were free and independent," historians write. But can a society be called free if it lives at the expense of the lack of rights of even a part of its members?

The poleis had not only their own government, courts and armies, but also their own patron gods. There were many gods, and the priests who served them did not enjoy such absolute and unquestioned authority as in Egypt or in Babylon, where the chief gods were single and obligatory for all. Nothing encourages free thought so much as the

absence of enforced unanimity.

The Egyptian priests knew this well. They concentrated all knowledge in their own hands, giving science a caste character and thereby shielding it from the people. In the lands of ancient civilisation, knowledge served religion. In the Greek colonies, however, science was from the very beginning secular.

"The Greeks did not create civilisation, nor even inherit it — they discovered it," writes J.D. Bernal in his book *Science in History*. Confronted with the powerful influence of the ancient civilisations of Mesopotamia and Egypt, they

> "selected from the cultures of other countries everything that, in their opinion, had value. In practice, any useful technical achievement was adopted, while in the sphere of ideas they were chiefly concerned with explaining the workings of the universe, discarding excessively complex theological constructions and the prejudices based upon them..."

Thus was born early Greek natural philosophy. Its greatest merit lay in the attempt to explain the world without any appeal to supernatural forces, to understand the nature of phenomena proceeding from the phenomena themselves — to conceive the world in the terms of everyday life and labour.

It should not be supposed, however, that all Greek sages categorically denied the gods. By no means. Most of them honoured the inhabitants of cloud-capped Olympus —

Zeus and Hera — sought the favour of Aphrodite, paid due respect to Ares and Dionysus, and bowed before Athena. They simply preferred to explain natural phenomena without the assistance of the Olympians. Nothing more.

1.3 Thales of Miletus

Between 624 and 547 before our era there lived in Miletus a man named Thales of Miletus. The son of a wealthy merchant, in his youth he travelled widely, engaged in trade, studied mathematics and astronomy with the Egyptians, and learned magic from the Chaldeans...

Having returned to his native city, Thales did not devote himself to commerce. Instead, he began to give advice, to reflect upon the nature of phenomena, and, somewhat in the manner of the Hebrew prophets, to preach his views before a small circle of disciples.

Thales taught that all that exists, the entire universe, is the result of natural qualitative transformations of a single substance. He regarded water as this primary principle of all things. It is not impossible that this reflects a connection between his doctrine and the cosmological notions of his Phoenician forebears, who considered the ocean the cradle of the world.

According to the Milesian sage, the Earth was flat and floated upon the surface of water. This enabled him to

explain earthquakes as the agitation of the deep waters beneath.

In general, a great number of discoveries and scientific truths have been attributed to Thales. It is all the easier to make such assumptions today because no one has ever read a single line of his writings. It is quite possible that he wrote nothing at all. In those days, people were far less inclined to write than they are now.

We call Thales a scientist because, according to tradition, he was the first to refuse the assistance of the gods in explaining the phenomena of nature.

The Milesian thinker, however, concerned himself not only with reflections upon "lofty matters". He did not disdain to offer practical advice as well.

A man would come to Thales and ask, "How may one live honestly?" And Thales would reply, "Do not do what you consider shameful in others."

A merchant, hesitant to set out upon a voyage, would seek his counsel — and here too the sage did not falter, for he possessed ample experience of travel and had something to recommend.

Before long, the authority of Thales of Miletus among his fellow citizens became extraordinarily high. It increased especially after a certain episode.

Having brought together the astronomical knowledge he had obtained from Egyptian priests, Thales once ven-

tured to predict a solar eclipse. Naturally, he was not believed at first. Nor were the Milesians much concerned. On that very day a battle between the Medes and the Lydians had been appointed, and the citizens of Miletus were animatedly discussing whether they should intervene in this foreign quarrel. Thales spoke decisively against war. The Milesians remained at home.

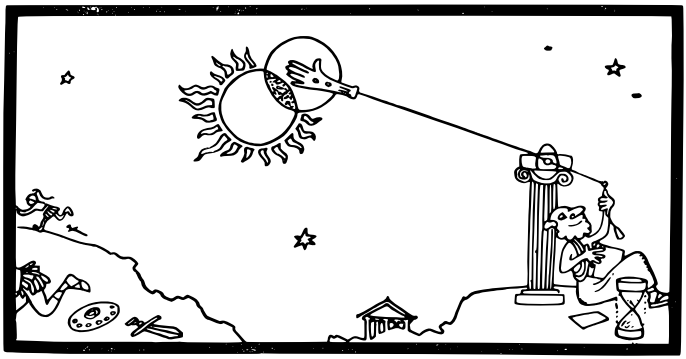
What happened next? Hardly had the bronze swords of the Medes clashed against the equally bronze shields of the Lydians when the sky began to darken. Across the bright face of Helios, the Sun, there crept a black shadow. Seized with terror, the warriors threw down their weapons and fled.

And the Milesians? Alarmed chiefly by the uncanny accuracy of Thales' prediction, they nevertheless found the courage to harness their chariots and ride out to the field of the battle that had not taken place. There they loaded their carts with abandoned equipment and even seized a number of neighbours who had failed to escape in time, promptly reducing them to slavery.

After this event the fame of Thales increased beyond measure. Having deliberated, the townspeople came to the sage's house and asked what reward he desired for his wisdom. Thales replied, "It will be enough for me if, when you speak of my discoveries, you say that they belong to me."

Unfortunately, sages are mortal just like all other people, even if they bear the mark of genius. Tradition relates that

during one of the Olympic Games the aged philosopher — who, incidentally, was a passionate supporter — became so excited by the victory of either his son or his grandson that he rose from his seat, cried "Glory!", and fell dead upon the stadium itself.



The townspeople buried Thales of Miletus. Upon his tomb they inscribed the words: "Small though this tomb of Thales be, great is the fame of this king of astronomers in the realm of the stars." And... they forgot. They forgot his counsel.

A younger compatriot of Thales, Anaximander (611–545 BC), reflecting upon the primary substance from which Thales had constructed the world, came to the conclusion that water would not suffice for this purpose. The substance of the world must, above all, be infinite, so that it should not be exhausted in the act of creation. And thus Anaximander proclaimed that the first principle is bound-

less and indefinite matter — the apeiron.

From this vague world-matter, in the philosopher's view, opposites such as the cold and the warm separated out. From their mixture arose the liquid. Thereafter everything proceeded much as in the teaching of Thales, though with certain slight deviations. From the liquid there further emerged the separate parts of the world: earth, air, and the fiery sphere that encompasses all existence...

Another representative of the Milesian school was Anaximenes (the dates of his life are uncertain, usually placed around the 53rd or 58th Olympiad, with 499 BC taken as the year of his death). Nothing is known of Anaximenes' life. Yet he rejected the abstract world-matter of Anaximander and returned to real air as the primary substance.

Anaximenes' view of world-formation is noteworthy. First, he considered the worlds to be numerous. Second, the worlds arose and perished, accomplishing an eternal succession, an everlasting cycle.

With the name of Anaximenes we must conclude our recollection of the Milesian school. Forgetting the counsel of Thales of Miletus and his appeals not to interfere in wars, the Milesians suffered a crushing defeat at the Battle of Lade in 494 BC. Thereafter Miletus was, in accordance with the customs of the time, utterly destroyed, and the Ionians lost their independence.

Thus the first stage in the development of Greek natural philosophy came to an end. An entire generation had to

pass before, in the neighbouring Ionian city of Ephesus, there appeared Heraclitus, who founded a great scientific doctrine...

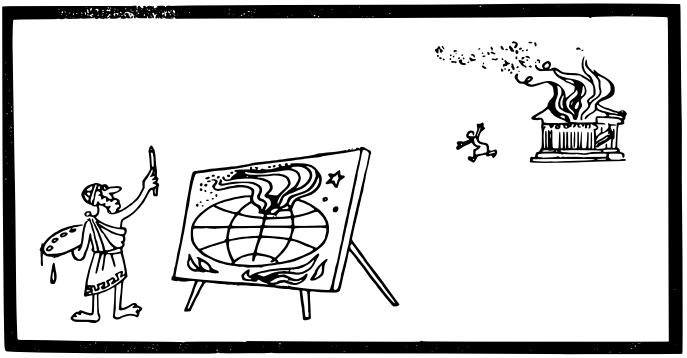
1.4 Heraclitus of Ephesus

Heraclitus of Ephesus (535–475 BC), son of Bloson, came from the most distinguished family of his city, tracing its line to the Codrids. One might object that the noble origin of a philosopher is of little importance — and in general that would be correct. Yet in this particular case it is not without significance.

The exact year of Heraclitus' birth is unknown, but his flourishing period is associated with the 69th Olympiad. It may therefore be supposed that he was born between 540 and 530 BC and lived for about sixty years, dying around 470 BC. By that time the Ephesians had overthrown the Persian yoke, and in the city the party that had carried out the liberation — the democratic party — was gaining strength. Heraclitus, however, stood on the side of the embattled aristocrats. After the democrats defeated the aristocratic party, he withdrew from political life, retiring into proud solitude and showing open contempt for the people. He repeatedly emphasised his disdain for the masses, setting his own judgement against the opinions of the crowd.

The remainder of his life Heraclitus devoted to study and reflection. His doctrine was far less transparent than that of his Milesian predecessors. Complex sensory images and a subtle play of concepts earned him among the ancients the epithet "the Obscure." He chose as his guiding maxim the saying "everything flows" and proclaimed as the fundamental truth the unceasing movement and

transformation of all things into one another.



As the symbol of universal movement, Heraclitus chose fire. For him, fire was the first principle — not as a substance, but rather as a process in which all things arise and pass away.

"Everything is exchanged for fire, and fire for everything, just as goods are exchanged for gold and gold for goods," he taught, and went on to express a striking idea:

> "This cosmos, the same for all that exists, was not created by any god nor by any man, but it always was, is, and shall be — an ever-living fire, kindling in measures and going out in measures."

Heraclitus developed an important idea concerning opposites. The presence within a single thing of two necessary opposites produced, in his theory, tension and the capacity for action. This philosophical notion may be illustrated by the image of a bow and its drawn string. The life

of nature, in Heraclitus' view, is a constant interweaving of opposites. It is from their conflict that individual things come into being. "Strife is the father of all and the king of all," he declared figuratively, perceiving the movement and development of the world as a process arising from the struggle of opposites, from inner self-motion.

Vladimir Lenin held Heraclitus' views in high esteem, noting that they provide "a very good exposition of the beginnings of dialectical materialism." In his work *Anti-Dühring*, Friedrich Engels wrote:

> "This primitive, naïve, yet in essence correct view of the world was characteristic of ancient Greek philosophy and was first clearly expressed by Heraclitus."

Although for a long time "birthmarks" of mythology remained within natural-philosophical cosmology, the creation of a picture of the universe without the intervention of gods was a supreme achievement of the thinkers of the Ionian school. Yet it was impossible to form a concrete image of the world from their teaching. Its character was purely descriptive, qualitative, and often contradictory. Their philosophy lacked a quantitative criterion. Without mathematics, it was helpless.

1.5 Philosophy + Mathematics = ?

Tradition maintains that the very first sage who called himself a philosopher — that is, a lover of wisdom — was Pythagoras. Apart from legends, we possess no reliable information about this figure, who remains popular even today. The Pythagorean school, however, is another matter. The Pythagorean brotherhood certainly existed and exerted considerable influence upon the further development of science.

It began, as so often, quite innocently. Legend attributes to Pythagoras the invention of the monochord, an ancient instrument for studying the vibration of strings. The Pythagorean Archytas used the monochord to determine the ratios of tones in musical scales. It was found that strings whose lengths stand in the ratios 1/2, 2/3, 3/4, and so forth, produce harmonious musical intervals.

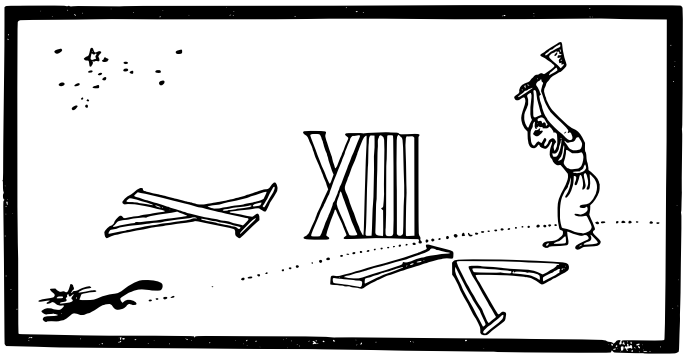
Does this suggest anything? Perhaps not at first glance. Yet had we belonged to the secret union of the Pythagoreans — and the school of Pythagoras was arguably one of the earliest secret societies in history — we should have heard numbers within the music itself. Divine harmony of sound was governed by mathematical laws.

Is not the harmony of sounds merely a particular case of the universal harmony of the world? Might not celestial phenomena also be linked with numerical proportions? Observe: the Sun rises and sets with unfailing regularity, as though governed by exact numerical laws. The Moon

just as precisely changes its phases. The planets wander across the sky... Are not numbers directing the motion of all things? Are not numbers the very essence of things?

The followers of Pythagoras were convinced that they had uncovered the secret of the life of the universe, and they set about developing this idea. Yet science was still frail. Facts were scarce, while the desire to comprehend the harmony of the world was intense. And so, in their imagination, the world was turned upside down. Numbers no longer explained phenomena — they ruled them. Mysticism began to emerge.

According to the Pythagoreans, numbers even possessed certain moral qualities: justice, soul, and the like. In this spirit, the numbers four and seven were regarded as principles of proportion and therefore of harmony, health, and reason.



Do not laugh, dear reader. Instead, ask your friends

what they think of the number thirteen, or whether they ever add together the digits on a tram ticket in order to discover whether they have received a "lucky" or an "unlucky" number.

There are certainly cases when, before some anxious event — an examination, for example, or a visit to the dentist — especially nervous individuals swallow a ticket bearing a "fortunate" number. This is no invention. On one occasion, having swallowed a splendid ticket numbered 841364, the author was at the very next stop escorted in disgrace to the police station, missed the examination, and in the register submitted to the dean's office there appeared opposite his name the note: "did not appear".

As is well known, the iron logic of a dean equates "did not appear" without discussion to the lowest mark. And that mark affects a scholarship as the sign *i* before a number transfers it into the realm of imaginary quantities.

And why did it all happen? The ticket was, after all, "lucky": 8 + 4 + 1 equals 3 + 6 + 4. Yet each fortunate half contained a clear warning: 8 + 4 + 1 makes thirteen, and 3 + 6 + 4 also makes thirteen.

After that, one may well hesitate before dismissing the magic of numbers altogether.

The Pythagoreans went further still. They revered not only numbers, but also constantly emphasised the importance of geometrical figures. They were especially devoted to the five regular solids, whose faces are composed of

triangles, squares, and pentagons. The embodiment of perfection in all existence, however, was the sphere — the divine and unsurpassed sphere.

Even an ideal love may bear fruit. Their devotion to the sphere influenced their conception of the structure of the world. Above all, the pupils and followers of Pythagoras firmly maintained that the Earth is spherical.

One might exclaim: compared with a flat Earth, this is clear progress. By what reasoning did they arrive at such an idea? Did the ancient Greeks, two thousand years before Ferdinand Magellan, sail around the globe in their clumsy galleys? After all, balsa rafts and papyrus boats have crossed oceans.

Yet history suggests that the Pythagoreans, like most Greeks, avoided venturing to sea unless compelled by necessity. The explanation was simpler. The sphere was the ideal figure. The Earth, striving towards perfection, ought therefore to resemble a sphere. That was sufficient.

The Pythagoreans conceived the universe as a highly ordered Whole functioning according to definite laws. Those laws, they believed, could be expressed only in the language of numbers and in mathematical forms. They praised in every manner the systematic and numerical harmony of the heavens. Most of them held that the Earth rests at the centre of the world, enclosed by the firmament — the sphere of fixed stars. What lay beyond that outermost sphere was of little concern. Sometimes it was described as the dwelling place of the gods; more often it was left

unspoken.

Among the followers of Pythagoras there was one philosopher whose views on the structure of the universe deserve special attention. His name was Philolaus.

Unlike his teacher and many other Pythagoreans, who divided the world into two entirely distinct parts — Earth and heaven — Philolaus maintained that the world is one and "began to be formed from the centre". At the centre he placed a certain "central fire". Around it, in his view, revolved transparent spheres bearing the Earth and the planets, as well as the fixed stars. Beyond them lay Olympus, the dwelling place of the gods.

The human body, Philolaus considered, is a prison of the spirit. Only particles of the divine fire, rising from the centre of the universe towards Olympus and entering human bodies on their way, give them life, harmony, health, reason, and an eternal striving towards the heavenly abode. Only when purified from material defilement does the soul ascend to the gods. For sinners, however, the path was different: their souls, weighed down by transgressions, descended into the lower spheres of inferior material existence and were reborn in the bodies of animals.

Philolaus counted ten divine spheres: the sphere of the Earth, the sphere of the Counter-Earth, the spheres of the Moon, the Sun, Mercury, Venus, Mars, Jupiter, Saturn, and finally the sphere of the fixed stars.

Ten! One of the important principles of numerical mysticism was thus preserved. Philolaus did not conceal his reverence for the divine essence of numbers. He was, after all, a Pythagorean. He was frank in this — unlike certain later "priests of science" who have been inclined quietly to transform God into a supreme mathematician, even attempting to confirm His existence by the equations of mathematical physics, while professing atheism.

Philolaus' Earth revolved around the central fire, turned towards it by its uninhabited hemisphere. That, in his view, explained why the inhabitants of the oikoumene[1] Today could behold only the reflected glow of the divine flame upon the smooth, polished surface of the Sun, which he believed to possess no heat of its own.

[1] *Oikoumene* (oikoumen•) is an ancient Greek term meaning the "inhabited world," traditionally referring to the known, civilized world, particularly the Roman Empire. Derived from *oikos* (house), it signifies the "whole inhabited earth". – DM

It must be admitted that Philolaus' system did not enjoy particular authority among his contemporaries. Even his own pupils, once they had left the school, promptly restored the Earth to its proper place at the centre of the universe. Yet a seed of doubt had been sown regarding the immobility and privileged position of the Earth among the heavenly bodies.

Nearly two thousand years would pass before that seed began to sprout. The shoot would make its way through the works of Plato and Aristarchus of Samos; in the Middle Ages it would cast a shadow across the treatises of the Central Asian thinker Al-Biruni; and it would finally see the light in the book *On the Revolutions* by Nicolaus Copernicus.

But before that moment, two thousand years still had to pass...

For the time being, however, the Pythagoreans enclosed the universe within the sphere of fixed stars, thereby freeing themselves from troubling thoughts about infinity. It seemed that infinity had been defeated and expelled. Yet this proved an illusion.

As the science of numbers developed, it gradually became clear that there is no greatest number. This was alarming, for it led straight back to the very infinity from which thinkers had tried to escape. Attempts were made to investigate infinity, even to measure it. It turned out that infinity overthrows common sense — so highly valued by the ancients and not unfamiliar to us today. However much one adds to or subtracts from infinity, it remains the same, immeasurable and equal to itself. Even the seemingly unquestionable axiom that a part is always less than the whole collapses when applied to infinity. Infinity revealed itself to be as treacherous as the Trojan Horse. Its paradoxes weighed so heavily in the balance that mathematics, once regarded as a "pure" science of number, became in large measure a science of infinity — a struggle that has not been conclusively won even now.

Much more could be said about the Pythagoreans. For the present, it is enough to note that with their school began a division in natural philosophy — and indeed in the whole system of human thought — into two irreconcilable directions. One, absorbing the abstractions of "pure" doc-

trine and mingling with mysticism, was later shaped by logic and came to be known as idealism. The other, combining the development of number theory associated with Pythagoras with the views of the atomists, evolved into materialism.

1.6 Elea: Xenophanes and Parmenides

By the fifth century BC, ancient Greek natural philosophy had accumulated so many ideas, insights, errors, and mutually contradictory views that open dispute became inevitable. These disputes led to what may be regarded as the first scientific crisis in the history of civilisation.

In Elea — a Greek colony on the south-western coast of the Apennine peninsula — the philosophers Xenophanes and Parmenides began to proclaim doctrines directly opposed to those of the Ionians.

Xenophanes (c. 565–473 BC) is usually considered the founder of the Eleatic school, which expressed the ideology of the conservative aristocracy. Strictly speaking, however, Xenophanes was not originally an Eleatic. Around 546 BC Ionia was invaded by the Persians, and many inhabitants were forced to flee their homeland. Among the exiles was the young rhapsode Xenophanes from the city of Colophon.

In ancient Greece, rhapsodes were professional performers and composers of epic poetry who earned their

living by their art. Travelling from city to city, they were welcome guests at festivals; townspeople greeted them with respect, and their songs remained long in memory. A rhapsode could just as readily glorify as ridicule the house and family of his host.

For more than seventy years Xenophanes led a wandering life, singing his verses throughout Greece. Only in extreme old age did he settle in Elea. In his poems he sharply mocked those who had imagined the gods in their own likeness, endowing the heavenly beings with all the habits and passions of human beings.

In the main, Xenophanes inclined towards materialist views, maintaining that everything which is born and grows is earth and water. The changing phenomena of nature he regarded as mere appearance, holding that the world is a single, unmoving whole which neither comes into being nor passes away, but remains eternally the same.

"The sea," he taught, "is the father of clouds, winds, and rivers. Men and animals were born of earth and water." Confirmation of the latter claim he believed he had found in fossils observed in Sicily.

His astronomical ideas were extremely naïve. He considered the Moon and the Sun to be fiery clouds that ignite at rising and are extinguished at setting. Living to the venerable age of ninety-two, he left many followers and thus laid the foundation of the Eleatic philosophical school.

A prominent representative of that school was Parmenides

(c. 540–480 BC). Parmenides was an influential figure in Elea, a city founded after his birth by Phocaeans who had fled from the Persians invading the coast of Asia Minor. His principal work, the poem *On Nature*, was written in response to the doctrines of Heraclitus.

Parmenides' cosmology in some respects resembles that of the early, spontaneous materialists. In principle, he was compelled to acknowledge motion and development. Yet unlike Heraclitus, who maintained that everything both is and is not — since all flows, all changes, and all is in a constant process of arising and passing away — Parmenides taught: "Being is; non-being is not, for it cannot be thought."

But if non-being does not exist, then change in the world is impossible. No thing can pass from one state of being into another state of non-being.

Parmenides was well acquainted with Pythagorean doctrine. Unlike the Pythagoreans, who conceived the world as consisting of a multitude of things arising and perishing, moving within the void that separates them, Parmenides declared that things divided by a void are a false conception.

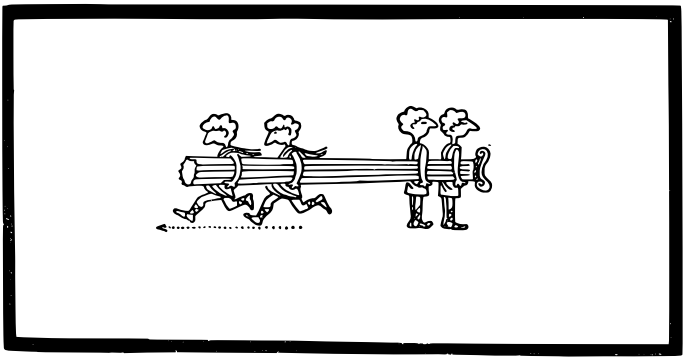
If the void is taken to be non-being, then it does not exist at all. But if the void is something that exists, what interval could be discerned between it and a thing — between being and being?

"That which is, is whole, one, and continuous," he wrote in his poem *On Nature*. True being is eternal, homoge-

neous, motionless, and unchanging.

These views led his followers to the radical denial of the possibility of movement altogether. No body can move to another place, because such a place simply does not exist. There is no void. Yet this raises an obvious difficulty: how can such a position be reconciled with observation?

In order to answer objections drawn from direct experience, the Eleatics maintained that our senses are deceptive.



Such open disregard for facts could not fail to provoke attention and criticism from contemporaries. Parmenides and his pupils found themselves in a difficult position. The apparent absurdity of their arguments seemed refuted by simple experience.

Do you recall the well-known lines?

> "There is no motion," said the bearded sage.
> Another held his peace and walked before him.

> No stronger answer could he have performed:
> All praised the subtlety of the retort.

These verses were written by Alexander Pushkin about the dispute between Parmenides' disciple Zeno of Elea and the Cynic Diogenes of Sinope.

Incidentally, Diogenes was not merely the man who lived in a barrel, shocked public morals, and in broad daylight "searched for a man" with a lit lantern. In keeping with the Cynic tradition, he rejected conventional virtues, condemned slavery, called labour a good, and treated religion with open contempt.

1.7 Zeno of Elea and His Paradoxes

Ancient philosophers repeatedly raised the question of how space and time ought to be conceived. Some held that they are infinitely divisible — continuous. Others maintained that space and time consist of certain smallest, finite and indivisible "atoms", that is, minimal segments or instants. Appealing to sensory experience, many philosophers were inclined to regard the observed picture of the world as true.

Then the brilliant disciple of Parmenides — Zeno of Elea (c. 490–430 BC) — demonstrated through logical arguments that discontinuity, multiplicity, and motion characterise only an unreliable picture of reality. *The senses deceive us; truth can be grasped only by thought*.

Vladimir Lenin highly valued Zeno's work, observing that "the philosophical significance of Zeno's aporias[2] lies in the fact that they revealed the real contradictions of motion, space, and time."

Motion, space, and time — together with matter — constitute the essence of the universe. And Zeno, despite the reactionary character of his general outlook, made a substantial contribution to dialectical reasoning.

The aporias of Zeno of Elea are such a brilliant display of logical reasoning, and they have played so remarkable a role in the history of civilisation, that one can scarcely refrain from presenting them.

The first is called the "Dichotomy." It asserts that it is impossible to traverse a finite distance within a finite time. To cover a certain distance, one must first pass half of it; to pass that half, one must first pass half of the half — and so on without end. Since this division proceeds to infinity, and it is impossible to pass through an infinite number of segments in a limited time, movement can neither be completed nor even begun.

The second aporia is "Achilles and the Tortoise." Here Zeno argues that the swift hero of the Trojan War, Achilles, will never overtake a tortoise given a slight head start. Each time Achilles reaches the point where the tortoise previously was, the tortoise has moved a little farther ahead. Thus, although the distance between them diminishes, it can never be reduced to zero.

[2] In philosophy, an aporia is a conundrum or state of puzzlement. In rhetoric, it is a declaration of doubt, made for rhetorical purpose and often feigned. – DM

In this way Zeno's reasoning seems to contradict even the vivid scenes described by Homer, where Achilles relentlessly pursues Hector around the walls of Troy, swift as a hound chasing a deer through mountains and ravines.

Logic, in Zeno's hands, appears to triumph over the evidence of sight — and therein lies both the power and the provocation of his paradoxes.

The second aporia is "Achilles and the Tortoise." In it, Zeno of Elea maintains that the swift-footed hero of the Trojan War, Achilles, contrary to Homer, would not overtake Hector...

> And Hector, fleeing, still was chased unceasing
> By great Achilles — as a hound upon the hills
> Pursues a young deer, roused from out its lair,
> And drives it on through thicket and through ravine;
> Even if the frightened creature crouch beneath a bush,
> The keen hound tracks and runs, nor ceases till he finds —
> So Priam's son from Peleus' son could not escape,
> Swift though he was...

Moreover, Zeno argued, the swift-footed Achilles would not overtake even a slow-moving tortoise. Each time Achilles covers the distance separating him from the tortoise, it will have crept a little farther ahead. Achilles will then traverse that new distance, and again the tortoise will gain a small advance. And so on without end.

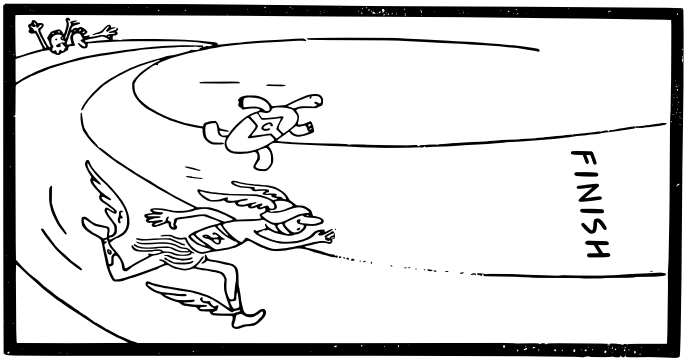
Both of these aporias are directed against the concep-

tion of space and time as continuous, infinitely divisible into ever smaller segments.

Two other aporias, with equal force, challenged the opposite view — that space and time are discrete, composed of indivisible units.

The third aporia is called "The Arrow."

A flying arrow is at rest, Zeno maintained, for at every given instant it occupies a space equal to itself and is at rest relative to that space. What is true at each individual moment of time must be true in general. Therefore, the flying arrow is motionless.



The fourth aporia is known as "The Stadium." Here Zeno of Elea sought to show that if motion is admitted, one must also admit that a unit is equal to its half. Imagine three equal rows of horsemen standing opposite one another. Now suppose that two of the rows begin to move in oppo-

site directions with equal speed, while the third remains at rest. After a certain time, the last riders of the moving rows will be opposite the middle of the stationary row. By that time, each will have passed half of the stationary row and the whole of the row moving in the opposite direction. In the same interval, therefore, a rider will have traversed both an entire length and its half. But that implies that a unit must be equal to its half...

The aporias of Zeno of Elea provoked more disputes in ancient scholarship than perhaps any other assertion. Thousands of years have passed. For many centuries, students across the world have confidently refuted Zeno in examinations at the insistence of their professors. And yet even today, in the opinion of distinguished mathematicians and philosophers, Zeno's aporias are not refuted completely — not "one hundred per cent." It is not difficult to refute them to ninety-nine per cent. But, on closer inspection, one discovers that the entire substance lies precisely in that unfortunate remaining one per cent. New difficulties arise before mathematicians; new contradictions give birth to new knowledge at a new, higher level.

Contradictions are the fuel of progress.

Academician Gustav Naan writes:

> "It is possible that humanity will never succeed in refuting the Eleatic 'one hundred per cent': infinity is inexhaustible, and Zeno... managed to grasp, in a naïve yet brilliant form, three 'eternal' problems, closely interconnected and bound up with the

> problem of infinity: the problem of nothingness, the problem of continuity, and the problem of existence."

In refuting Zeno, the philosopher Democritus — a representative of the atomist school — taught that all bodies consist of an imperceptibly large number of imperceptibly small, mathematically indivisible particles — atoms. From similar elements is composed the segment of the path in Zeno's "Dichotomy." Into such elements time itself is likewise resolved. The relation of the small segments of the path to the equally small intervals of time is finite and determines the speed of motion. Achilles will inevitably overtake the tortoise, Democritus concluded.

Within his reasoning lay the germ of the great idea of the calculus of infinitesimals — an idea realised nearly two millennia later by Isaac Newton and Gottfried Wilhelm Leibniz.

1.8 Atomists and the very first "scientific" cosmological hypothesis

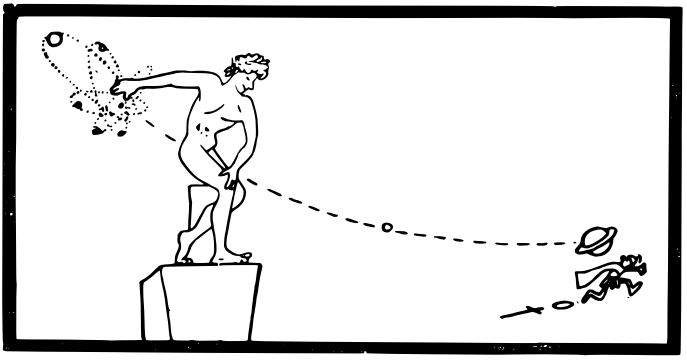
From the works of Democritus (c. 460–370 BC) almost nothing has survived to our day. The materialism of this philosopher was so detested — first by the adherents of Pythagorean–Platonic idealism, and later by Christian priests and monks — that they destroyed Democritus' books wherever they found them. We learn of his views and teachings from the writings of other authors. Thus the historian

Diogenes Laertius states that Democritus' finest work was the *Megas Diakosmos* — "The Great World-System." In his book *Lives of the Philosophers*, this historian sets out the cosmological ideas of both Democritus and his teacher Leucippus.

> "He says that the universe is infinite... One part of it is the full, the other the void; these he calls the elements; and from them arises an infinite number of worlds. The worlds come into being in this way: separating out from the boundless, a multitude of bodies of various shapes rushes into the great void. Gathering together, they produce a single vortex, in which, colliding with one another and whirling about in every manner, they become separated, and like moves toward like.
>
> ...Thus the finer bodies withdraw to the outer regions of the void... while the rest 'remain together' and, intertwining with one another, move collectively and form first a certain spherical compound..."
>
> ...Thus the Earth also arose, because the masses borne to the centre "held together." The very periphery, formed in the manner of a shell, continued to increase through bodies separating from without. Carried along by the vortex, it attached to itself whatever it happened to touch. From these, certain interlacings of bodies formed a compound which at first was very muddy and moist; later these bodies dried and revolved together with the cosmic vortex; then, having been set alight, they formed the nature of the heavenly luminaries...

The reader may well complain of the obscurity of this

exposition. In defence, one may say only this: these lines represent one of the earliest natural-philosophical cosmological hypotheses known to humanity. They are about two thousand years old.



Many centuries would pass, and in the seventeenth century the principal theses of Democritus would be repeated and developed by René Descartes; another century later, Immanuel Kant and Pierre-Simon Laplace would do the same independently of one another. And if one were to cast aside the mathematical superstructures even of the most modern theory — still only being born under the pen of some unknown genius — would it not appear that, in our understanding of the world as a whole, we have not travelled so very far from the views of that ancient Greek materialist in a ragged chiton and sandals on bare feet? The Greek who exclaimed:

> "...nothing arises from non-being, nor is resolved into non-being... Not a single thing arises without cause,

> but everything arises on some ground and by necessity!"

In the hypothesis of Democritus, as in the views of his teacher Leucippus, there was not a word about gods. Hence no supernatural forces took part in organising order out of chaos. To draw such a conclusion more than two thousand years ago was no easier than it is today to take part in a discussion of an anisotropic cosmological model of the universe. To begin any undertaking is always more difficult than to continue it at whatever stage.

1.9 Summa summarum of Greek materialism

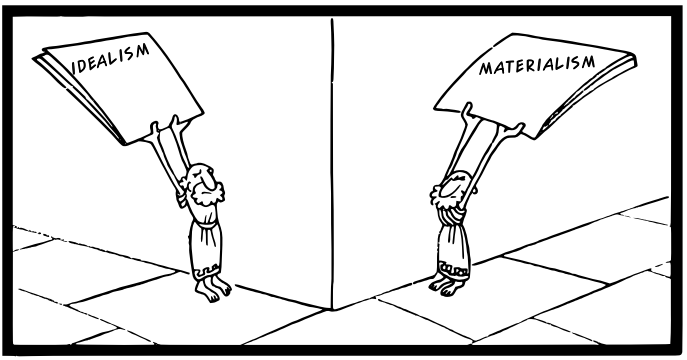
The atomistic theory was so bold and so openly materialist that, perhaps precisely owing to the hatred of the idealists, we have become acquainted with many of the views of Leucippus, Democritus, and Epicurus (341–270 BC). Their own writings have not come down to us, having been destroyed by those in power who adhered to idealism. Yet the criticism and abuse directed against the atomists — scattered generously throughout the works of the proponents of the doctrine of the ideal — provide an impression of the godless positions of these militant radicals. Even the authority of Plato and Aristotle did not succeed in burying the stubborn heresy of the materialists.

Atomism in ancient Greece inspired Pierre Gassendi

and Isaac Newton, John Dalton and Mikhail Lomonosov. It became the direct progenitor of all modern theories of the atom.

In concluding our consideration of this doctrine, it is worth pausing briefly over Epicurus. His views were so thoroughly materialist and so openly irreligious that they became the object of hatred among idealists of every age. The Roman philosopher and poet Lucretius (99–55 BC) expounded the ideas of Epicurus in his poem *De Rerum Natura* ("On the Nature of Things").

Today this literary work is not easy reading, and therefore the author has permitted himself to borrow from it those lines which convey an impression not only of the philosopher's own views — so to speak, at first hand — but also of the entire sum of ancient Greek materialism accumulated before Aristotle.



Here is what Lucretius writes in the fifth book of his

poem, which concerns us directly, since he speaks there of cosmology.

> ...There was only chaos, and some wild tempest...

Gradually, however, the primal chaos in the poem begins to assume order: "the like to enter into union with like."

> ...Then the lofty sky began to part from the earth,
> And the seas withdrew, set apart within their watery bounds.
> ...In those times the ether too, likewise fluid and light,
> Bending into a vault, enclosed our world in compact mass
> And, spreading everywhere, diffusing in every direction,
> Held all the rest fast in its eager embrace.

Having sketched the origin of the Sun and the Moon, Lucretius turns to the principal object of his concern — the Earth — and, having formed it through pressure and a "hail of blows," the poet once more returns to the universe, though now upon another level.

> ...It is perhaps difficult to determine what cause operates in this
> World; yet what is possible and what occurs
> In the different worlds of the universe, fashioned on differing principles,
> This I set forth, and I expound the series of causes
> By which the motion of the heavenly bodies may be accomplished in the vault of heaven...

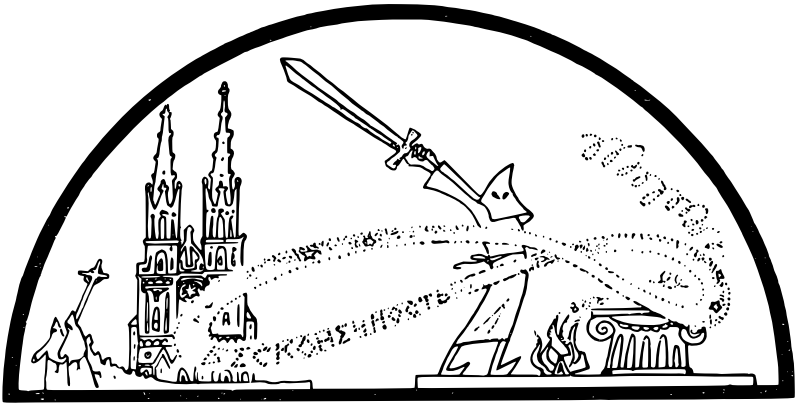
Here lies the central substance of the atomists' worldview: the infinity of space and the plurality of worlds in the universe, "fashioned on differing principles." Democritus and

Epicurus attempted to unite into a single dialectical whole, and to reconcile, two opposing philosophical conceptions: the flux and perpetual motion of the Ionian Heraclitus, and the stability and logical rigour of the Eleatic Parmenides.

Many theories were advanced by the ancient Greeks. In them one may discern the seeds of almost all those ideas which not only yesterday, but today and tomorrow, appear to us bold and innovative.

Why, then, did they sink into oblivion, replaced not by a flourishing of civilisation but, on the contrary, by a sombre age of faith — by the near two-thousand-year triumph of dogma[3] over reason?...

[3] Dogma, in its broadest sense, is any belief held definitively and without the possibility of reform. It may be in the form of an official system of principles or doctrines of a religion, the positions of a philosopher or philosophical school, and political belief systems. In the pejorative sense, dogma refers to enforced decisions, such as those of aggressive political interests or authorities. More generally, it is applied to some strong belief that its adherents are not willing to discuss rationally. – DM



2. The Philosopher King of Physics

> From which the reader may quite independently conclude that progress is by no means directly proportional to time.

The intellectual achievements of the ancient Greek thinkers before Aristotle lacked a system or a framework.

There were isolated facts, principles, and individual hy-

potheses. The greatest possible contribution to the general development of science would have been a classification serving as a foundation for uniting what had been achieved into a coherent whole.

It is true that any classification carries within it certain dangers, for it creates an impression of completeness and finality, and may close the path to further development.

Yet this conclusion still had to be reached. In the fourth century BC, classification and logic were as necessary to science as air itself. And then Aristotle appeared. One should not forget, however, that heroes do not arrive by chance or from nowhere. They are summoned forth from non-being by their age.

2.1 Aristotle

Much has been written about Aristotle — so much that today it is almost impossible to separate truth from invention, fact from legend.

It is reliably known that Aristotle was born in Stagira, a city of ancient Macedonia, into the family of a physician. In childhood he was surely taught respect for nature, as befitted a descendant of Asclepius, the patron of medicine.

At the age of seventeen Aristotle moved to Athens, where for twenty long years he was a pupil of the philosopher Plato. The spirit of objective idealism that reigned in the

Academy must have turned the young man away from the views instilled in him at home. It is not impossible that at first this was indeed the case. The works written by the Stagirite in that period concern chiefly such abstract disciplines as rhetoric and logic. Yet the more mature Aristotle became, the more independence he displayed in discussing his teacher's philosophy.

When, in his later years, Plato withdrew into logical speculation and romantic allegory, calling upon his pupils to renounce the reality of the sensible world in favour of "pure thought" and the "ideal prototypes of the visible world," Aristotle broke with him and opposed the entire system of objective idealism. "Plato is my friend, but truth is dearer still" — these famous words, attributed to Aristotle, have become a proverbial formula of intellectual separation.

From this point onward, in Aristotle's views there begins to crystallise a harmonious union of abstract logical analysis with close attention to the phenomena of nature. After Plato's death Aristotle left Athens and returned to his homeland. In 343 BC King Philip II of Macedon summoned him to court and invited him to become the tutor of his thirteen-year-old son, Alexander (who later becme Alexander the Great). The philosopher accepted the proposal and, replacing the previous instructor, remained constantly at the side of the future founder of a vast empire.

Three years later, however, the sixteen-year-old Alexander was compelled to take up affairs of state, and two years

after that he won his first battle at the head of his father's troops. The philosopher and his warrior-pupil parted for good. Alexander departed on his campaigns, while Aristotle, generously rewarded by him, returned to Athens, where he founded a school to rival Plato's Academy — the **Lyceum**.

There, walking along the shaded paths of the garden, he taught his pupils in the mornings; after the midday meal he delivered public lectures open to all who wished to attend, and engaged in debates and disputations with philosophers of other schools.

Legend has handed down to us an image of Aristotle as a small, frail, and singularly unattractive man, with a perpetual sardonic smile upon thin lips. He is said to have spoken with a lisp. In his dealings with others he was cold and haughty. Few dared to enter into dispute with him. His biting and mocking speech struck without mercy. He dis-

mantled the arguments of any opponent — logically, wittily, and ruthlessly. Nothing remained to be set against him in debate, nothing that might secure even an honourable draw. No, Aristotle struck to kill.

Such a manner won him few friends. When his patron Alexander the Great died, many rejoiced at the opportunity to settle accounts with the philosopher. He was accused of impiety.

This was the most common accusation not only in antiquity. It has always stirred the sympathy of the masses and has been almost impossible to defend against. In modern times it has been replaced by equally demagogic slogans — "disloyalty", "a crime against the nation, against the people" — a collection of wretched sophisms by which rulers have sought to govern public opinion.

Aristotle understood the difficulty of his position. Before his inward eye stood the fate of Socrates, who by sentence of a prejudiced court received a cup of poison. And, "to spare the Athenians a second crime against philosophy," Aristotle fled from the city and from Greece, withdrawing to a colony in Asia Minor. It availed him little. Having been poisoned, according to some accounts, by fish eaten at table, he soon died. The will of the gods was fulfilled — so the legends say.

The range of the philosopher's genius is truly astonishing. His multi-volume works *Organon*, *Posterior Analytics* and *Topics* are devoted to logic; the *Metaphysics*, in twenty books, and many other writings concern philoso-

phy. His *Physics*, *History of Animals*, and the treatise *On the Heavens* speak for themselves. Aristotle also left works on psychology and history, ethics and aesthetics, politics, rhetoric, poetics, and many other branches of knowledge.

From this list alone it is easy to see that Aristotle can scarcely be regarded as a solitary thinker. His remarkable organisational abilities and skilful direction of his pupils enabled him to become the true head of a school. Only the carefully guided labour of a large collective can explain the quantity and diversity of scientific material presented in Aristotle's writings. Thus, if Plato's Academy may be called the first university in human history, then Aristotle's Lyceum may be regarded as a prototype of the scientific research institute.

Karl Marx once called Aristotle the Alexander the Great of Greek philosophy, meaning that if the conqueror subdued the world by force of arms, the philosopher did so by the power of thought.

In constructing his system of the universe, Aristotle gathered together the whole sum of accumulated knowledge, considering it dialectically from the standpoint of common sense. In doing so, he unhesitatingly rejected ideas of his predeessors which, from the perspective of the twentieth century, appear progressive.

His universe is an eternally living and purposively functioning organism. It has always existed and will exist forever. Aristotle restored to the Earth the position of centre of the world, rejected the doctrine of its motion and the

notion of a plurality of worlds as concepts lacking direct evidence and difficult to grasp. In their place he constructed a cosmological scheme of a universe spatially finite yet eternal in time.

This universe comprised a series of concentric celestial spheres, ultimately set in motion by a divine "prime mover". The scheme was simple. It outlived not only its creator but, for nearly two thousand years, dominated science and unfortunately hindered its further development.

2.2 The Triumph of Aristotelianism

The cosmological ideas of Aristotle prevailed for many centuries. They overcame both the views of the Pythagoreans and the later progressive heliocentrism of Aristarchus of Samos; they suppressed with equal success the materialism of Democritus and the idealism of Plato, setting in their place orthodox and comparatively limited conceptions.

According to J.D. Bernal, one of the reasons for this lay in the difficulty of understanding the conceptions of the ancient Greek thinkers. He writes

> "No one could understand them, except very well-prepared and experienced readers, and such readers were not easy to find in the early Middle Ages. The works of Aristotle, however, for all their bulk, did not require — or seemed not to require — anything beyond common sense for their comprehension. Aristotle, like Hitler, never said anything that his hearers

> would not readily believe. There was no need for experiments or instruments to verify his observations; no difficult mathematical calculations or mystical intuition were required to grasp any inner meaning... Aristotle explained that the world was just as everyone knew it to be. Like Jourdain in *Le Bourgeois gentilhomme* by Molière, they were all philosophers without knowing it."

Moreover, none of the ideas of the ancient philosophers had ever been clothed in so coherent and rigorous a system of argument as that of Aristotle.

His cosmological conception was not only vivid, comprehensible, and familiar to ordinary experience. It was closely connected with his investigations into motion, space, and time, and seemed open to confirmation by the simplest experiments and the most superficial observations.

Aristotle wholly rejected the views of the Ionian school, which had taught the idea of the world's coming into being. In his opinion, the world had always been as we now see it. There was no need for its creation.

This doctrine of the eternity of the universe later proved highly inconvenient for the Christian Church, when Aristotelian teaching was adopted as the philosophical foundation of Catholic ideology. The Church therefore "corrected" the philosopher, declaring the world to have arisen from nothing "by the will of God" and foretelling its destruction for the same reason at the end of its appointed term. This was the only substantial amendment introduced into

Aristotle's cosmology during the two thousand years of its dominion.

Particularly convenient for the future Christian Church proved to be Aristotle's idea of the innate striving of the rational part of the human soul towards perfection. Aristotle wrote: "We must feel love for the higher when we behold it." This "obligatory love" permeated all levels of relationship in his system: that of slave to master, wife to husband, and human being to God.

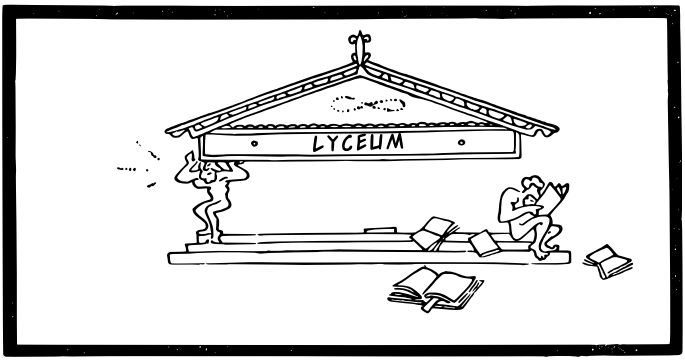
It was this conception of an eternal and ordained order that secured for Aristotle's philosophy the support of medieval clerical scholastics, who transformed his living philosophical teaching into a rigid and lifeless orthodoxy. "Scholasticism and priestcraft took what was dead in Aristotle, not what was living," wrote Vladimir Lenin.

If one attempts to probe the deeper causes of the triumph of Aristotelianism, one arrives at the conclusion that the historical limitations of the slave-owning order could hardly fail to lead to orthodoxy — to blind adherence to established principles. Bertrand Russell wrote:

> "Philosophy taught men to accept life as it is, and offered nothing to those who found it intolerable except the doctrine that their sufferings were inevitable and part of the great order of nature. Such a philosophy was on the road to becoming a religion — but a religion in the interests only of the upper classes."

Slave-owning society held labour in contempt. Yet science, without labour and without experiment, is deprived

of its chief support — the possibility of repeating and verifying conclusions. It would be inaccurate, however, to say that in the age of ancient Greek civilisation practice was wholly neglected. Though the Greeks despised manual work, their era is remembered not only for worldviews. The block and lever, the pulley and compound tackle, the well-sweep with counterweight, scales, the crank, the potter's wheel, the centrifuge, and gear transmission — together with Archimedes and his dozens of mechanical inventions, and Hero of Alexandria with his fire engine and steam device — all belong to the Greeks.



Yet the principal wealth of ancient Greece lay, of course, in its philosophical doctrines. Friedrich Engels wrote in *Dialectics of Nature* that "in the manifold forms of Greek philosophy there are already contained, in embryo and in the process of formation, almost all later types of worldview."

The heliocentric tendency in Greek thought has already been mentioned more than once. It found particularly convincing expression in the work of Aristarchus of Samos (310–230 BC), an outstanding astronomer and geometer who was the first to attempt to determine the distances to celestial bodies from observational data.

Having measured the apparent diameter of the Sun and calculated that its distance was nineteen times greater than that of the Moon, he concluded that the Sun was far larger than the Earth in volume. He also maintained that the stars were much farther from the Earth than the Sun. Moreover, as a follower of Pythagorean teaching, Aristarchus boldly placed the Sun at the centre of the world, set the Earth spinning upon its axis like a top, and caused it to revolve around the Sun in an orbit.

Historians today possess only one work by Aristarchus of Samos — *On the Sizes and Distances of the Sun and Moon*. For nearly twenty centuries his calculations were regarded as a "reliable" component of astronomy. It scarcely occurred to anyone to test their accuracy. Yet in his own time Aristarchus' ideas brought him considerable trouble. As was to be expected, a defender of divine authority appeared. This was the Stoic Cleanthes[4], who accused Aristarchus of impiety.

The heliocentric idea, lacking obvious supporting evidence, found few adherents. Nevertheless, the assertion that not the Earth but the Sun was the largest body in the universe was highly progressive for its age. Might not the

[4] Cleanthes (c. 330 to 230 BC), of Assos, was a Greek Stoic philosopher and boxer who was the successor to Zeno of Citium as the second head of the Stoic school in Athens. – DM

views of Aristarchus of Samos have inspired Archimedes in his attempt to calculate the dimensions of the universe?

Thus, in concluding with Aristarchus of Samos the fortunate epoch of Greek intellectual development, one is tempted to call upon the reader to marvel at their achievements and to exclaim:

> "Glory to the Greek philosophers! Hail to the wise sophists! To the Ionians, the Pythagoreans, the Eleatics and the atomists, the austere Cynics and the cheerful Cyrenaics, the Peripatetics, the Stoics and the Epicureans, the sceptics, the gnostics, and all the rest."

Having done so, one may proceed boldly to the next historical stage — perhaps not so radiant as the ancient Greek and Hellenistic periods in science, yet of profound importance for what follows.

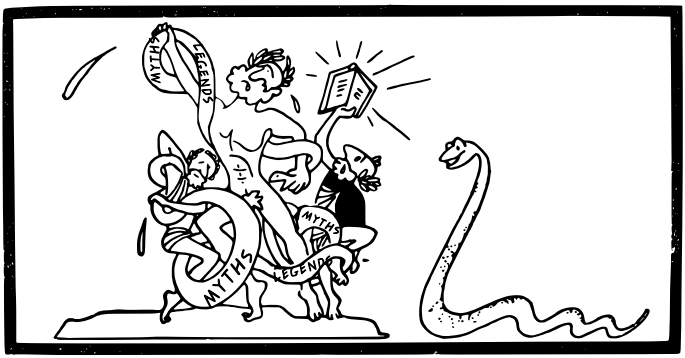
2.3 At the Decline of Classical Greco-Roman Culture

After the death of Alexander the Great and the brief flourishing of the new capital of his empire — Alexandria — the situation in the world changed. The divided Greek state yielded primacy to the powerful military Rome. Greece itself became one of the provinces of the new empire.

The elite Roman legions pushed the frontiers ever farther, making them seemingly boundless. After sixteen, or

even twenty or twenty five years of service, discharged soldiers returned home, telling tales of the mists of the British Isles and the impassable marshes of the upper Nile, of the hardships of guard duty at the Pontus Euxinus — as the Black Sea was then called — and on the shores of the Hyrcanian (Caspian) and Red Seas.

Look at a map and imagine these vast spaces without railways or paved roads, without aeroplanes or motorcars. Try to picture a time when the swiftest means of travel was a horse, and you will understand that the territory of the Roman Empire was simply too large.



The conquests of the Romans, unlike the campaigns of Alexander the Great, brought little that was new to the subjugated peoples. Rome possessed no highly developed culture of its own with rich traditions. The transplantation of Greek culture onto Italian soil came too late.

First, Greek civilisation itself was already declining. Secondly, although the upper classes of Roman society adopted the ceremonial and outward splendour of Greek culture, they inwardly despised their teachers. For example, the founder of Roman prose literature and a prominent statesman, Cato the Elder, hated Greek science. Throughout his life he fought against Greek education, believing that philosophers merely corrupted the Romans.

From ancient times science has been compared with light, for knowledge illuminates the traveller's path. This comparison has not lost its force. Yet another property of light may also be applied to science. The reader is, of course, familiar with the photon — the elementary particle of light, possessing both corpuscular and wave properties. One of its characteristics is that its rest mass equals zero. In order to exist, it must move continuously. Is not science similar?.. Knowledge that does not develop begins to decay and eventually disappears.

What practical application could the slave-owning system give to the discoveries of the Hellenes or the Romans? Labour was the lot of the slave. Hence the contempt for those who sought to adapt knowledge to the needs of practical life, the denial of the role of experiment, and the veneration of dogma.

We say that astronomy developed from the needs of navigation. Yet the Greeks possessed few ships capable of venturing into the open sea. It was the Phoenicians who travelled. The indolent Romans preferred, to the risks of

distant journeys, the reading of the translated *Odyssey* of Homer. The genuine knowledge of the philosophers found no application and was gradually consigned to oblivion. Little by little, myths and legends once more took the place of natural-philosophical hypotheses.

Of course, the work begun by the philosophers could not cease at once. For some time it continued by inertia. But what were the results of the long and complex path of Greek, Hellenistic, and Roman astronomy?

Around 280 BC, Aristillus and Timocharis compiled the first star catalogue in Europe. About 230 BC, the Alexandrian astronomer Eratosthenes, observing the shadow of a gnomon in Syene and Alexandria, determined the circumference of the Earth. He calculated it as 250,000 Egyptian stadia — approximately 45,000 kilometres.[5]

In the period roughly between 180 and 125 BC lived Hipparchus — the greatest astronomer of antiquity. He compiled the first lunar and solar tables, invented several astronomical instruments, and introduced a system of geographical coordinates for determining the position of a point on the Earth's surface. Hipparchus prepared a star catalogue describing the positions of 1,022 stars and discovered the precession of the equinoxes.

Finally, in 46 BC, at the direction of Julius Caesar, the Alexandrian astronomer Sosigenes of Alexandria carried out a reform of the Roman calendar. It was decided that the year should begin on 1 January. The reckoning according to the Julian calendar began on 1 January 45 BC.

[5] Other estimates of Eratosthenes' measurement put the value of his circumference to 40,338 km, remarkably close to the modern day measurement of the circumference around the equator is 40,075.017 km.

The new era did not mark its arrival with any remarkable scientific achievements. Around the year 150, Claudius Ptolemy composed his *Almagest*[6] — originally entitled *The Great Mathematical Construction of Astronomy in Thirteen Books*. This work, later named *Almagest* by the Arabs, remained until the mid-sixteenth century the most complete astronomical encyclopaedia. Ptolemy finally confirmed and formalised the geocentric scheme of the Aristotelian universe.

The reader may expect at this point a vivid portrait of the great astronomer of the ancient world. Yet such a portrait cannot be drawn. At the very beginning, it was solemnly promised not to rely on material lacking historical authentication. Neither his appearance nor a single trait of his character has survived; even the exact dates of his birth and death are unknown. Only his thirteen books remain.

Ptolemy refined and extended the theories of his predecessors, added his own observations, and brought the theory of epicycles to such perfection that astronomers, using the geocentric system, were able to perform certain practical astronomical calculations. From that time, perhaps, there arose the tendency to assume that the greater the role of mathematics in science, the more precise science becomes — and that precision corresponds directly to truth.

We shall encounter again the situation in which the most diverse and mutually incompatible hypotheses agree equally well with observed phenomena, until some ex-

[6] The name Almagest is a fascinating linguistic hybrid that reflects its journey through history. It originated from the Greek title H=e Megist=e Syntaxis (The Greatest Compilation), but when medieval Arabic scholars translated the work, they added the Arabic definite article "al-" to the Greek "megist·". This resulted in the Arabic name al-Majis··, which was eventually Latinised into the title we use today. – DM

perimental evidence tips the balance in favour of one of them.

For us, what is especially important is that the aim of Ptolemy's titanic labour was to establish the foundations of a *geometrical picture of the world*.

Ptolemy's work "was a carnival procession of geometry, a festival of the profoundest creation of the human mind in its representation of the universe," wrote the distinguished Dutch astronomer and historian of astronomy Anton Pannekoek.

The life and activity of Claudius Ptolemy unfolded during the fortunate reigns of the emperors Hadrian and Antoninus Pius. The Roman Empire seemed to rest from the chaos of incessant wars, struggles, and economic difficulties. From the outside it might have appeared that ancient society had entered a bright era of peaceful development, that a golden age of great Hellenic culture had arrived.

Yet this was not so. Historians maintain that by the time of the fall of the Roman Empire, the way of life of its peoples differed little from that of the Bronze Age, which had ended two thousand years earlier. And this after Homer, Thales of Miletus, Democritus and Plato, after Socrates, Aristotle, after Epicurus...

Barely a century passed before a raging storm shattered the mighty empire. Another century later, the entire culture of the ancient world had been forgotten.

2.4 Zigzag of History

At the beginning of the new era, ragged men appeared in the Roman catacombs calling themselves Christian apostles. They gathered around them gladiators and slaves and delivered sermons. To people weary and longing for truth, they spoke of supreme justice. They proclaimed a single true God for all — for the rich and the poor, for patricians and slaves... Such a new and unusual idea drew crowds to their preaching.

The apostles taught that life should not be cherished, for every sufferer was promised a splendid existence beyond the grave. Gradually the Christian sect became a powerful and indestructible organisation, founded upon blind faith in the teaching of the apostles.

The emperors dealt cruelly with the Christians. They were thrown into cages with wild beasts, killed in the arenas of circuses, crucified upon crosses... Nothing availed.

The Christians grew ever more numerous, ever stronger. They began a counter—struggle against paganism[7]. Incited by fanatical bishops, their crowds destroyed temples, shattered sculptures and monuments, naively believing that they were annihilating idols.

The leaders of the early Christians were by no means the most educated people of their time. Unable to comprehend the wisdom contained in the ancient books, they led frenzied mobs to plunder the Library of Alexandria.

[7] In early Christianity, paganism (from Latin: *paganus*, "rustic") collectively referred to the diverse religious practices of all people who were polytheists. More specifically, it denoted anyone who did not adhere to a Abrahamic religion in the Roman Empire. – DM

They kindled bonfires from "pagan" manuscripts. Over the long years of Roman rule the crowd had grown accustomed to spectacles, and the power—hungry patriarchs of Christianity directed the energy of obedient people against all that they themselves hated. And what does a limited mind hate first of all? That which it does not understand. Thus the patriarchs, by the hands of Christians, devastated observatories and killed scholars who, in the old manner, still honoured the former gods...

At the turn of the fourth and fifth centuries, there lived in Alexandria the first woman astronomer, mathematician, and philosopher known to history — the daughter of the mathematician Theon. Her name was Hypatia. By the age of forty-five, several works by Hypatia of Alexandria were already listed in one of the Byzantine lexicons. None of these writings has survived.

In 415, a mob of enraged Christians, driven to the ex-

treme of fanaticism by preaching monks, "burst into her house, dragged the unfortunate woman out, and tore her beautiful body to pieces before Patriarch Cyril had time to intervene..." Most likely, the patriarch did not hasten. Hypatia did not profess the merciful Christian doctrine.

Such events would be repeated more than once in the course of history. Each time those involved would believe they were carrying out their own will, while in reality they were merely instruments through which greedy, cunning, and energetic nonentities forced their way to power.

Christians lit the first bonfires of books. The fathers of the Inquisition took up the torch from the hands of the patriarchs. And when religion yielded its place to politics, the fascists likewise marked their ascent to power in 1933 with the same festival of flames.

To burn books is the surest sign of cultural decline. Remember this:

> "Burning was a pleasure. It gave one a special delight to see things consumed by fire, to watch them blacken and change... his hands, turning torn and charred pages of history into ashes, seemed like the hands of a strange conductor performing a symphony of fire and destruction... He walked amid a swarm of fiery red sparks, and what he most desired at that moment was what he had so often done in childhood — to thrust a stick with a sweet into the flames, while the books, like pigeons rustling their wings—pages, died upon the porch and the lawn before the house; they rose in a fiery whirlwind, and

the wind, black with soot, carried them away."

This is Ray Bradbury, an American writer. The book that opens with this terrible paragraph is entitled *Fahrenheit 451*, and it bears the explanation: "451 degrees Fahrenheit — the temperature at which paper ignites and burns." The book is dedicated to the future of America.

2.5 When the Flames of Bonfires Do Not Dispel the Darkness of Night

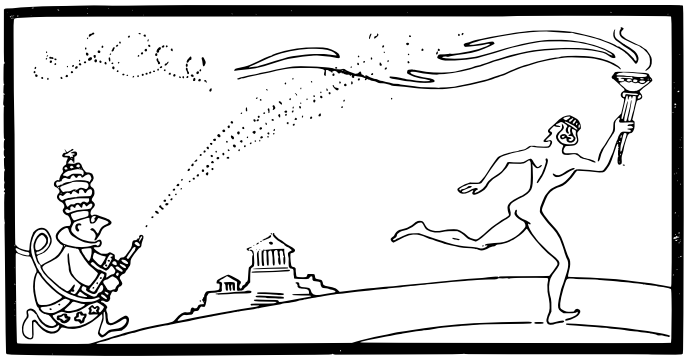
At the end of the fourth century, the last Roman emperor, Theodosius I, issued an edict against the pagans. An edict was a decree of special importance proclaimed by the emperor. Henceforth and for ever, sacrifices and visits to pagan temples were forbidden. Temple property was confiscated in favour of the state, and the buildings themselves were to be destroyed. The Christian faith alone was declared true and permissible — and only in the form accepted in Rome.

In 382, Theodosius uttered for the first time the fateful word "inquisition", which in Latin means "investigation". Although the Inquisition as an institution was established much later, the word itself became for many centuries a sombre companion of the Christian Church.

The decree did not remain mere ink upon paper. Soon, in the city of Trier, the first bonfires were lit, upon which

those who refused to submit to the shepherds of Alexandria or Rome were burned alive. The heretics who perished were themselves Christians, differing from Rome in such minor matters of faith that today these disputes would scarcely be intelligible to us. Yet the Catholic Church would tolerate no dissent whatsoever.

From that moment the "sun of intellect" over Europe began swiftly to set. From the hall of the Senate in Rome the famous statue of Statue of Victory was removed and broken up, declared an idol of pagan belief. In 394, the last Olympic Games were held in Greece. In the same year Christian bishops extinguished the eternal flame in the temple of Vesta — guardian of the hearth.



Year after year the slime of indifference choked the springs of knowledge. If the first Christians could at least not be denied courage, the situation changed once Christianity became a force. It began to attract adventurers

and greedy men, people who recognised only one god — wealth. The episcopal rank[8] no longer meant the arena of the Circus with wild beasts, nor a cross by the roadside. It now meant riches, glory, and power.

Ignorant men, elevated not by knowledge or ability but by intrigue and baseness, began to claim the title of the sole and infallible teachers of the Church. Yet authority over the intelligent and the learned is a precarious construction. And so these ignorant but cunning "teachers" proclaimed as truth only what they themselves declared. Those who disagreed were branded heretics and sent to the stake.

The noble human impulse to investigate the surrounding world was declared sinful by the Fathers of the Church. "Ignorance is the mother of piety; reason comes from the devil," they taught.

The very first attack was directed against the philosophical inquiries of the ancients and their views on the structure of the world. "Is it possible," wrote one of the zealous champions of the new religion, the bishop Lactantius[9], "that men should be so mad as to believe that crops and trees hang downwards on the other side of the sky, and that people there have their feet higher than their heads?..." And all agreed with him: "Of course, it is impossible!"

Augustine of Hippo, one of the most renowned teachers of the Western Church, stated plainly that the existence of people on the opposite side of the Earth was impossible, since this was not mentioned in Holy Scripture. These were fearful words, giving rise to the dogma: "Whatever

[8] In the early Christian era, bishops (episcopal rank) faced martyrdom in brutal Roman spectacles like the Circus arena with wild beasts or roadside crosses. By late antiquity, after Christianity's legalization under Constantine (313 CE), the role evolved into one of immense wealth, prestige, and political influence. – DM

[9] Lactantius (c. 250 – c. 325) was an early Christian author who became an advisor to Roman emperor Constantine I, guiding his Christian religious policy. – DM

is not in Scripture is heresy!" Such a position is enough to extinguish in anyone the desire to pursue science. The acceptance of such a dogma is equivalent to throwing open the door into emptiness...

Having secured primacy in the spiritual sphere, the Church cast ever longer glances toward secular power. Friction began between kings and popes. At first, all bishops were called "papa". But from the fifth century onward this honorary title was applied chiefly to the Archbishop of Rome.

2.6 The Principles of Papal Infallibility

Historians of the Catholic Church often describe the history of the papacy as though the supreme shepherds of Christianity — the Roman popes — were wise and benevolent men of ascetic life. One of the principal distinguishing features of Catholicism is the recognition of the Roman pontiff (the pope) as the "Vicar of Christ — the Son of God on Earth", infallible in matters of faith.

The popes repeatedly intervened in questions concerning the science of the universe. Let us, for a moment, set aside scientific matters and consider what these "wise and humble vicars of the merciful Christ on Earth" were like in former times. The reader may then draw conclusions independently.

In 955, the son of one of the wealthiest Roman senators,

Octavian, was raised to the papal throne. He took the papal staff and ruled the Church under the name of Pope John XII. At that time Octavian — John XII — was sixteen years old. Yet even at this youthful age he was already deeply corrupted. Within a year, a delegation of Romans went to the emperor Otto I with complaints against the young pope.

The envoys declared,

> "He is the devil!" "And like the devil, he hates the Creator. He profanes holy things; he is intemperate; justice does not exist for him... To satisfy his whims he resorts to sacrilege and murder. He is a violator and an incestuous man. All honourable Roman women — maidens, wives, and widows — flee from Rome lest they become his victims. The papal palace, once an inviolable sanctuary, he has turned into a brothel..."

In those years emperors still possessed the authority to appoint and depose popes. Otto I immediately ordered that a special council be convened, at which the most prominent churchmen were to examine the conduct of the young pope. Many Italian, German, and French clerics were present.

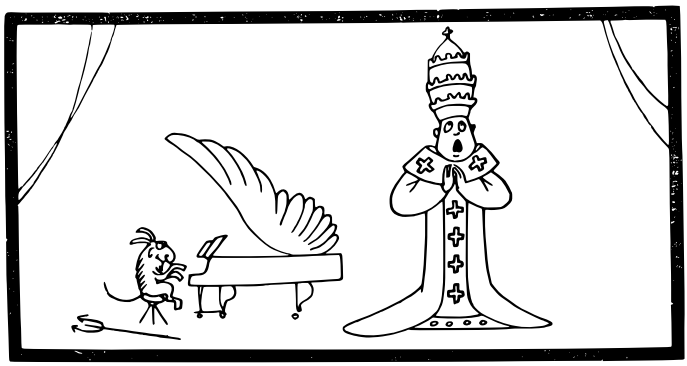
At first 'minor' accusations were brought against the pope. He was charged with never making the sign of the cross, with appearing before the faithful in military armour, with frequently going hunting in suspicious company, with habitual profanity, gambling at cards, and invoking the pagan gods Zeus and Aphrodite to help him win.

Then more serious accusations followed. He was accused of drinking to the health of Satan — and witnesses were cited who had been present.

Cardinal Giovanni and the Bishop of Nantes charged Pope John XII with having elevated one of his favourites to the episcopal rank in a stable. He was accused of selling church offices and of establishing fixed payments for elevation to ecclesiastical rank.

It was said that the pope had, for money, consecrated a ten—year—old boy as a bishop...

In short, the offences were so numerous that the council resolved to depose him. In his place another was elected, who took the name Pope Leo VIII.



After the emperor withdrew his troops from Italy, the subdued former pope, Pope John XII, together with a band of loyal companions and drinking associates, burst into

Rome and seized the papal throne by force. The unfortunate Leo VIII — himself hardly a model of virtue, yet defeated — had his tongue and nose cut off and his fingers severed. Cardinal Giovanni lost a hand, and the Bishop of Nantes was, by the pope's personal order, flogged.

John then convened a new council at which he compelled those present to address him as "Most Holy", "Most Blessed", "Most Venerable", and "Most Good". Yet he did not alter his manner of life and soon died under rather unusual circumstances. In the evenings he visited a beautiful Roman woman. Her husband, discovering the affair, lay in wait and beat the pope so severely that he died a week later in terrible agony, without even receiving communion.

His successor, Pope Benedict VI, ended his life strangled in prison. The next pope was likewise murdered.

Indeed, in the history of the papacy few of the supreme shepherds died a natural death. Rope, poison, and imprisonment were the customary fate of adventurers who seized the apostolic throne.

Particularly notorious in the fifteenth century was Antipope John XXIII. The son of wealthy parents, he had long been, in his youth, an outright brigand — a pirate who plundered merchant ships and coastal settlements.

The popes were unwilling to yield to kings in anything. They maintained armies and seized extensive territories. Exploiting the superstition of an ignorant populace, they devised numerous means to intimidate and deceive or-

dinary people. Thus excommunication was introduced. The excommunicated person was cursed from the church pulpit, forbidden to attend divine services, and after death even denied burial in consecrated ground. He lost all civil rights, could not participate in public life, and was placed outside the law. People avoided him in fear. No one was permitted to offer him hospitality, a drink of water, or a piece of bread. Yet anyone was free to kill him without fear of punishment, for the killing of an excommunicated person was regarded as a deed pleasing to God.

Even more dreadful was the interdict — a curse imposed upon an entire country for disobedience to the pope. All church services ceased. According to eyewitnesses, the situation became terrifying. The dead were not buried; children were not baptised. A deathly silence prevailed everywhere. Ignorant and therefore especially devout people fell into despair and became capable of anything... Any king would accept the deepest humiliation rather than risk the imposition of an interdict. Thus, little by little, kings became obedient servants of the popes.

Impunity led to the corruption of the entire Catholic clergy. Drunkenness, debauchery, and ignorance among churchmen were combined with greed. The holy fathers were so absorbed in personal affairs and quarrels that they even neglected the persecution of heretics. This condition bore particularly heavily upon science. Knowledge accumulated by previous generations fell into final decline. Fragments of truth, once wrested from nature by ancient philosophers, were replaced by open inventions

proclaimed as truths if they corresponded in any way to the legends of Holy Scripture.

2.7 The Fathers of the Catholic Church and Progress

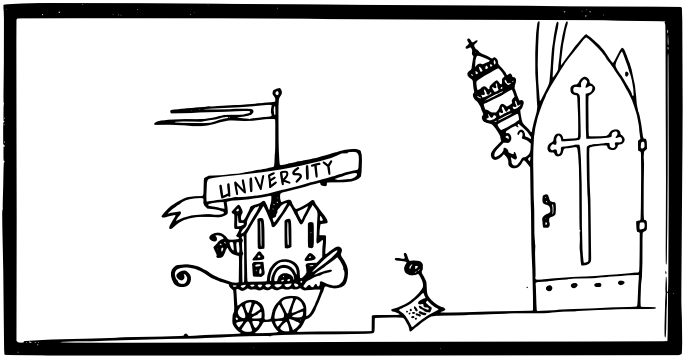
Classical Greco-Roman culture perished as the Church grew in power. Yet human thought could not remain long in stagnation. With the disappearance of natural philosophy, it sought ground within religion and mysticism. Opportunities were abundant. Devils, witches, and other dark forces filled the world, serving as catalysts for alchemical reactions and astrological predictions.

And yet the longing for truth cannot be extinguished. Gradually and almost imperceptibly, this need turned the interests of magicians, astrologers, and alchemists once more toward science. The road, however, was long. The peoples of Europe had too thoroughly replaced pagan civilisation with orthodox Christianity.

Only in 1175 was Ptolemy's *Almagest* translated again from Arabic into Latin and restored to Europe. It is difficult to imagine how greatly progress would have been delayed had the peoples of Asia not preserved fragments of classical achievement during the age of faith in Europe. Astronomy survived, although in the Muslim world its results were also used chiefly for the compilation of horoscopes.

The history of science is a splendid testing ground for dialectics as an instrument of inquiry. Throughout the centuries opposing currents and mutually exclusive hypotheses constantly arose. These deeply hostile conceptions never coexisted peacefully. They struggled against one another, justifying the title "Drama of Ideas" given to science by Albert Einstein.

If the dogmatism of the Christian Church replaced the fallen civilisation of the Greeks, heresies simultaneously began to develop within it, undermining the foundations of dogma. To combat heresy, the clergy required education. Yet learning cannot coexist comfortably with dogmatism. So it has been, and so it will be...



By the twelfth century universities began to appear in Europe. The first was the University of Bologna around 1088, followed by the University of Paris with its recognition in 1160, then the University of Oxford (teaching by

1096, organized c. 1167), and the University of Cambridge in 1209.

The principal task of the universities was the training of the clergy. Students, clad in long robes, learned to speak and write in Latin, studied arithmetic, geometry, astronomy, and music, and finally proceeded to philosophy and theology. As books were exceedingly scarce in the early Middle Ages and fabulously expensive, instruction was conducted orally in the form of lectures.

Public disputations were also widespread during these years. Church fathers who had become acquainted with ancient culture attempted to incorporate certain elements of Hellenic philosophy into the dogmas of Christian teaching. This gave rise to heated debates in which each side asserted its orthodoxy while accusing its opponents of heresy. In 1276, Pope John XXI wrote on this matter:

> "... from high and influential persons I have received information that certain teachers in the faculty of arts, exceeding its bounds, expound in their lectures various absurd and impious propositions as though they were doubtful and open to disputation."

No, the Church did not encourage disputations, preferring to resolve dangerous questions at closed episcopal councils. Yet gradually public debates became one of the favourite forms of entertainment. The names of learned and successful disputants were spoken with respect. Disputes were arranged even at royal courts...

> In the palace at Toledo
> Trumpets call all to the gate,

> Crowds in motley colours gather
> For the disputation great.
>
> In this battle there assemble
> Not young paladins in line;
> Here the adversaries shall be
> Capuchin and learned rabbi.

So begins the poem *Disputation* by Heinrich Heine, describing a controversy between representatives of different religions.

It is true that if scholarly disputations sometimes assisted in the birth of at least some fragment of truth, theological debates more often ended without result. Unless, of course, one considers sufficient the conclusion of that same poem:

> ..."I do not know who here is right —
> Let others judge between;
> But rabbi and Capuchin
> Smell equally unclean."

In our own day, a disputation — even a scientific one — rarely has decisive significance. That is regrettable. Representatives of different schools and directions prefer "peaceful coexistence" precisely where a clash of opinions would be far more appropriate. In the twentieth century the art of debate somehow fell asleep. One hesitates to pronounce the word "died".

We have forgotten how to speak extempore, how to speak without a prepared note. Even seasoned wits sometimes confess: "The improvisation was written yesterday."

Public defences of dissertations, with official opponents present, thanks be, almost never develop into genuine disputes. And yet it is a pity that the art of arguing, of speaking eloquently in defence of a chosen position — an art once so highly developed among the Russian intelligentsia (recall the final debate between the professors Nikolay Kostomarov and Mikhail Pogodin on the origin of the Varangians[10]) — has been lost by our students, by their professors, and by their teachers alike...

In the fifth century, Augustine of Hippo, one of the most prominent theological thinkers, postulated that God and the world are inseparable. All that exists is a kind of emanation of God. Even time itself was created at the moment when the world was created.

Augustine of Hippo examined in detail one of the most controversial questions of his time: the relation of man to divine grace. The learned bishop maintained that man is capable of receiving this grace, thus shaping a kind of compromise between faith and philosophy. This was understandable. The son of a Christian mother and a convinced pagan father, Augustine — then still called Aurelius — led in his youth a thoroughly worldly and dissipated life.

Having received a sound classical education, he spent his days in a whirl of pleasures, moving from Carthage to Madaura, carefully avoiding his native Tagaste — ancient cities of North Africa. Pagan authors, in particular Cicero and Plato, stirred in him an interest in philosophy, and only at the age of thirty-three did he accept Christianity. There-

[10] In 1869, Ukrainian historian Nikolay Kostomarov and Russian scholar Mikhail Pogodin debated the Varangians' origins—Viking (mostly Swedish) warriors and traders who shaped Kievan Rus' from the 8th–11th centuries—with Kostomarov claiming Slavic roots and Pogodin Scandinavian ones. This clash reflected 19th-century nationalist tensions over Eastern Slavic ethnogenesis. – DM

after he advanced rapidly and became bishop of Hippo.

Augustine's compromise doctrine did not endure for long. One heresy after another arose, each setting itself the task of refuting his dogmas, and until the very Reformation a continuous struggle was waged against the teaching of Saint Augustine.

Later, the celebrated scholastic and theologian Thomas Aquinas repeatedly attempted, within the framework of the prevailing theological worldview, to reconcile faith and reason, developing in his treatises problems of space and time. Yet all these efforts did not go beyond purely speculative reasoning. In the search for the supreme goal — the salvation of the soul — empirical confirmation of theories was simply unnecessary. Religion preferred to deal with myths, and for the suppression of doubt and the calming of excessive curiosity there existed such powerful weapons as faith and the Holy Inquisition...

2.8 The Gloomy Middle Ages and the Development of Technology

The Church and the Inquisition succeeded in establishing a strict order in the medieval world. Everyone knew his place. Society as a whole was rigidly subordinated to a fixed hierarchy. At the head of secular life stood the emperor, followed by kings, nobles, and finally the lowest estate — the common people. The same structure pre-

vailed in spiritual life. The head of the Church — the pope — was surrounded by cardinals, bishops, archbishops, and an innumerable army of clergy and monks descending in rank.

A similar hierarchy existed in the picture of the universe shaped in that epoch. At the centre of the world stood the Earth, encircled by the spheres of the Moon, the Sun, and the planets, to which angels of various ranks were attached, charged with maintaining proper order among the heavenly bodies. Beyond the outermost sphere of the "fixed stars" lay heaven, the abode of God. In opposition to this celestial grace there was the subterranean hell, arranged in comparable spheres or circles, only descending in the opposite direction. Thus, if the vast, bright, and spacious heaven beyond the firmament belonged to God, the narrow and fetid centre of the Earth was the domain of Satan...

The temptation to pursue the comparison further — to set the nine choirs of angels against the circles of hell — is strong. Yet five centuries earlier this had already been done by the incomparable Dante Alighieri. The reader who has reached this point may turn to the pages of *Divine Comedy* and, if not read them in full, at least glance at the illustrations by the great draughtsman Gustave Doré.

Yes, the universe seemed constructed solidly, rationally, and for eternity. Christian dogmas were skilfully combined within it with the most logical conclusions of the ancient authors, and nothing appeared capable of shaking this

massive edifice.

True, various schools continued to arise, each interpreting certain details in its own way. Yet even in their heretical teachings the main structure remained unchanged. Moreover, heresy was swiftly and efficiently neutralised. The ideology of medieval society was astonishingly monolithic. The existing picture of the world was threatened from another direction.

We are often unjust when we speak of the Middle Ages as a time of complete and universal stagnation. And yet this long and indeed rather sombre period in human history was marked by many remarkable technical inventions. Technological innovations increased productivity, enlarged the surplus product, and gave rise to a new class of entrepreneurs, thereby contributing to the decline of feudalism. The emerging bourgeoisie required a new philosophy — one capable not only of seeing further than medieval scholasticism but also of accomplishing more...

To avoid being unfounded, let us recall several technical improvements and innovations dating back some eight or nine centuries. First of all, energy. The principal mechanism for converting the natural energy of water into mechanical power was the mill, invented, according to Vitruvius, in antiquity. Yet in the slaveholding system, to grind grain it was sufficient simply to summon a slave. Only in the Middle Ages did watermills become widespread. (In England alone there were more than five thousand.)

By the middle of the twelfth century windmills — in-

vented in Persia — also appeared in Europe. These mechanisms "automated" such processes as fulling cloth, operating bellows, and forging iron with hammers. In addition, at the beginning of the eleventh century horseshoes and the horse collar, which replaced the ancient strap harness, came into use in Europe. These inventions made it possible to increase a horse's load fivefold, to replace the slow ox, and consequently to expand grain production and trade across the continent.

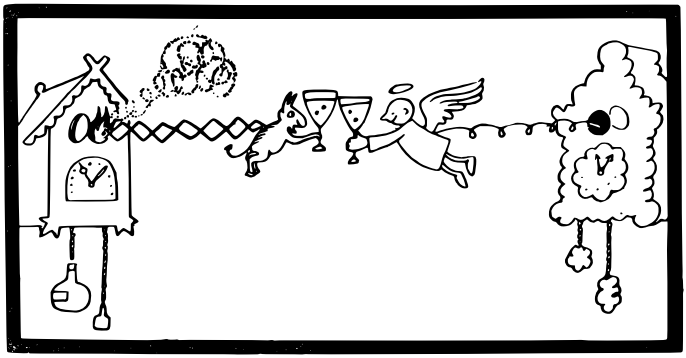
Blacksmiths, whether members of urban guilds or villagers, found their workload increasing. The construction and maintenance of mills, dams, and sluices required new knowledge. Gradually, some blacksmiths became millwrights — mechanics. It was these mechanics who built the first clocks in the cities of Europe.

Strictly speaking, "the clock as such", like the wheel, is an invention for which it would be difficult to claim a patent. From the papyri of Ancient Egypt we know of sundials. Water clocks were almost certainly used in Ancient Babylon for astronomical observations. Clepsydras and hourglasses were known in classical Greece, where time was measured either by the rising level of water in a receiving vessel or by weighing it. The Arabs improved the Greek water clocks, transmitting the movement of the liquid level by means of floats and cords to indicators in the form of hands.

In European cities up to and including the eleventh century, time was determined by the ringing of the town

bell, struck by the watchman. Among his duties was also the keeping of time by means of sand or water clocks and turning the vessels at the proper moment.

In the countries of the northern latitudes there was less sun, and in winter water froze into ice. Then it occurred to one of the mechanics to replace the lowering of the water level in a clock by the descent of a weight, transmitting this motion to the hands through toothed gears. The result was a mechanism resembling a pendulum clock. Further improvements followed, and the mechanism itself began to strike the bell. Thus were born the mechanical clocks — the pride of medieval cities.



Thus there emerged the profession of the clockmaker — the future reserve of skilled craftsmen, inventors, and later engineers.

By the thirteenth century European ships were equipped

with a stern rudder and both fore and aft sails. This made it possible to sail not only with a strictly favourable wind but also at an angle to it. At the same time European seafarers adopted the compass, long known in Asia, now in the form of a needle mounted on a pivot, as well as the chart marked with a wind rose. Navigation on the open sea demanded further advances in astronomy and raised the problem of determining longitude — a problem not solved until the eighteenth century[11]

[11] The problem of determining longitude while at sea was a difficult problem with very interesting history. It effectively led to several innovations in technology of measuring time by leading to construction of "sea-worty clocks". The longitude problem was effectively solved in 1761 by John Harrison. – DM

Finally, it was in the Middle Ages that such inventions as gunpowder and cannon penetrated into Europe. This brought about a genuine revolution in military affairs and had a profound effect on the politics and economies of European states.

It is curious to note that the distillation of strong wine spirit also dates from roughly the twelfth to fourteenth centuries. At first it was used as an extremely rare medicine. But during the plague epidemic that ravaged Europe in 1348–1349 — the period later known as the **Black Death** — demand for alcoholic drink increased enormously. People believed that one who drank *aqua vitae* — the "water of life" — could never be seized by the pestilence. Spirit began to be produced and consumed in vast quantities.

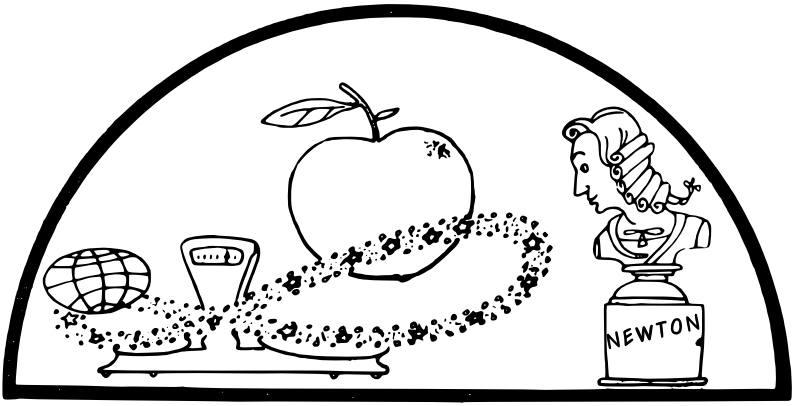
Gunpowder and spirit — could one imagine a more "reliable" foundation for progress? And yet the production of alcohol did indeed stimulate science, creating conditions for the later emergence of organic chemistry and the physics of heat. In the aggressive colonial expansion of

European states, however, gunpowder and spirit were to play a tragic role.

In the twelfth century, thanks to the Arabs, paper also appeared in Europe. In regions rich in flax and textiles its production proved so inexpensive that a shortage of book copyists was soon felt. This, in turn, led in the fifteenth century to the rapid spread in Europe of printing techniques — first using movable wooden type, and later metal type — inventions that had been developed many years earlier in China and Korea.

As a typical example of what we would now call feedback, the appearance of printed matter — prayers, sacred books, and indulgences — gradually contributed to the liberation of the mind from ecclesiastical control. It required literacy not only from monks but also from craftsmen and prepared the ground for the coming Reformation.

For astronomy, which depended upon observation, such a technical improvement as spectacles was of particular importance. Their manufacture and use also began in Europe around the middle of the fourteenth century, although the properties of lenses had been known long before. The growing demand for spectacles led to the development of the profession of lens grinders. This development later, in turn, resulted in the creation in 1609 of the first telescope by Galileo Galilei. Yet between that moment and the period we are describing there still lay such an epoch as the Renaissance.



3. The Art of the Great Discovery: From Cusa to Calculus

In which the author, continuing his journey into the past, pretends to be briefly acquainted with the authorities.

The Renaissance began with a criticism of the entire picture of the world. "Everything that Aristotle taught is

false!" — this famous thesis was proclaimed from a university chair of Paris in 1536 by the humanist Peter Ramus. People, weary of the hopeless despair of the final centuries of ancient classicism and of the humility and renunciation of earthly joys during the age of faith, seemed to awaken from a heavy sleep. Concern for the present replaced the former preoccupation with the afterlife.

Secular arts flourished. "Do what you please," taught in his books the wit — and, according to some accounts, a stout and gluttonous man — Alcofribas Nasier, whom the impoverished patients of the Lyons city hospital revered as Doctor Monsieur François Rabelais. The lists of bold adventurers honoured as discoverers of new lands grew longer. And is it really so important today that the son of a Genoese weaver, Christopher Columbus, engaged in sea raiding in his youth? Or that the first English circumnavigator, Francis Drake, was a corsair — and not only in his reckless early years?

It was a restless yet hopeful time. "Thrones are shaking, minds are in turmoil, science rushes into battle — how splendid it is to live, yes, how splendid to live in these years, my friends!" wrote the German humanist Ulrich von Hutten.

To this same remarkable epoch belongs a new page in the history of ideas about the universe.

3.1 Cardinal Nicholas Krebs of Cusa

"God, in creating the world, employed arithmetic, geometry, music, and astronomy — all the arts which we too apply when we investigate the relations of things, elements, or motions," wrote the outstanding Renaissance thinker Nicholas of Cusa (c.)in his treatise *On Learned Ignorance*.

> "By means of arithmetic God made the world into a single whole. By means of geometry He gave things form, stability, and motion according to their conditions. By means of music He bestowed such proportions upon things that there is as much earth in earth, as much water in water, as much air in air, and fire in fire. He so arranged it that no element could be entirely dissolved into another; from this it follows that the machine of the world cannot wear out and perish..."

Nicholas of Cusa (his real surname was Krebs) was born into the family of a fish merchant in the village of Kues in southern Germany on the Moselle. Hence the name "Cusanus", which accompanied him throughout his life. In those years people were often identified by the names of their places of birth. This, first, expanded the modest possibilities of medieval nomenclature and, secondly, immediately provided information of considerable importance at the time — a person's territorial origin.

A tradition has been preserved that even in early youth the restless son of the fish trader ran away from home, where he was expected to inherit his father's apron. A

local noble benefactor is said to have helped the boy by placing him in the school of the "Brethren of the Common Life" in the ancient town of Deventer.

After completing his studies, Nicholas moved to Padua, to the renowned University of Padua, and in 1424 defended his doctorate in canon law, at the same time entering the Augustinian monastic order. Before long, the fame of the young expert in ancient philosophy — who combined its popular ideas with those of the waning Middle Ages — spread throughout the papal monarchy.

The transitional period leading into the Renaissance demanded compromises with the orthodoxy of the departing age. Nicholas of Cusa was among the first to strive for reconciliation between the most extreme positions.

With the accession of a new pope, Pope Eugene IV, an ecumenical council was convened in Basel — the Council of Basel. There, important ecclesiastical matters were to be decided: the limitation of papal authority, the struggle against heresy, the moral corruption of the clergy, the conclusion of peace with the moderate Hussites and the so-called Utraquists, and other such issues.

As an expert theologian, Father Nicholas of Cusa was summoned to Basel. There he made the acquaintance of the noted humanist and papal legate Giuliano Cesarini and formed a friendship with him.

With the support of an influential patron, Nicholas of Cusa spoke publicly for the first time with a position of

his own, skilfully attuned to the atmosphere of the council. As a learned theologian he called for reform within the Church, yet as a supporter of the papal party he argued for reform without weakening central authority.

Recognising Rome — the "See of Saint Peter" — as the spiritual centre of the universal Church, he cautiously denied the pope's authority over secular government and, together with others, condemned abuses such as interdicts and financial manipulations.

However, when the assembly split and the majority turned against Pope Eugene IV, Nicholas of Cusa, along with Cesarini and other "humanist progressives", alarmed by what they regarded as revolutionary demands, withdrew from the council in the pope's company. Eugene IV attempted to dissolve the council and convene a new one at Ferrara. The defiant majority refused to submit. Indeed, those remaining in Basel elected another pope in place of Eugene — the aged Duke Amadeus of Savoy, who assumed the name Antipope Felix V.

Yet a divided papacy suited neither princes nor kings, and Felix V won little recognition. Meanwhile Nicholas of Cusa, as a scholar of Greek, travelled to Constantinople as envoy of Eugene IV to negotiate union with the rulers of the Eastern (Byzantine) Church. After the council that began in Ferrara and concluded a year later in Florence — the Council of Florence — he returned to his native Germany as prior of a monastery in Melnfeld and was appointed visitor of the monasteries along the Rhine and the Moselle.

It was during this period that he wrote his celebrated treatise, from which the quotation at the beginning of this account was taken. A few years later Nicholas of Cusa was elevated to the rank of cardinal-priest of the Roman Church and appointed Bishop of Brixen in Tyrol.

This was the most fruitful period in the life of Nicholas of Cusa. He wrote extensively, devoted himself to philosophy and mathematics, and studied the astronomical treatises of the ancients. His works and ideas contributed greatly to shaking the foundations of scholasticism, opening and indicating new paths for the scientific understanding of the world.

On the one hand, he still remained an absolute scholastic, accepting only what accorded with the "unshakable" dogmas of the Church. He was a prominent theologian, philosopher, cardinal, and associate of the Pope. Yet on the other hand, he was a mathematician and an astronomer. His astronomical ideas are striking in their fertility. He categorically denied that the Earth is the centre of the world and allowed for the possibility of its motion around the Sun, formulating clearly, for the first time, the principle of the relativity of motion.

> "We already understand that the Earth in fact moves, although this does not appear so to us, for we perceive motion only by comparison with a fixed point. If someone did not know that the water was flowing, did not see the banks, and were on a ship in midstream, how could he perceive that the ship was moving? For the same reason, if anyone were upon the Earth, or upon the Sun, or upon any other planet,

> it would always seem to him that he was at the unmoving centre and that all other things were in motion... The machine of the world has, so to speak, its centre everywhere and its circumference nowhere, because God is both circumference and centre, being everywhere and nowhere..."

Indeed, if one sets aside the reference to God as a concession to the spirit of the age, what stands before us is a thoroughly rational and strikingly modern view of the universe.

In his work *On the Correction of the Calendar*, Nicholas of Cusa proposed his own method of improving the calendar — a method that in its results was entirely analogous to the later Gregorian reform introduced under Pope Gregory XIII. In the same treatise one may also discern, though not yet in a fully explicit form, the hypothesis of the Earth's sphericity and its rotation about its axis.

True, these suggestions lacked any physical demonstration; they were, rather, a return to the views of the ancient Greek thinkers. Yet they are important to us as evidence of the ideas that were soon to find full expression in the work of Nicolaus Copernicus — ideas that at the time were, as it were, "in the air".

Ah, doubt — a dangerous force. Its attraction is so powerful that even a theologian seasoned in disputation, the cautious Cusanus, was carried further. From his hints he proceeded to the infinity of the universe in space and time and even mentioned the plurality of worlds... A century and

a half would pass, and these same ideas — now developed and gathered into a coherent, openly heretical system — would lead another thinker to the stake...

The contradictory philosophical ideas of Nicholas of Cusa produced many followers. If you encounter the names of Jacques Lefèvre d'Étaples, the Sorbonne humanist, or his ardent pupil Charles de Bovelles (who signed his works as Carolus Bovillus), or the legendary Gerolamo Cardano, and finally Giordano Bruno, remember that all these distinguished historical figures — philosophers, thinkers, mathematicians — were convinced adherents of the teaching of Nicholas of Cusa, the first philosopher of the Renaissance. The list of his followers might easily be continued.

3.2 On the Banks of the Cosmological Rubicon

The turn of the fifteenth and sixteenth centuries gave humanity more than all the time that had passed since the appearance of the *Almagest* of Claudius Ptolemy. With the change in the picture of the world, the place of man in the universe also changed — his role and his significance in his own eyes. Few events have so profoundly influenced the subsequent development of culture.

In truth, the preparation for these changes had begun long before — perhaps as early as the era of the Crusades, when the naïve and primitive notions about the shape and

composition of the Earth were first seriously challenged. Yet the knights set out on their campaigns with little burden of knowledge. Piety and greed took the place of curiosity.

Then came Marco Polo, Vasco da Gama, and finally Christopher Columbus. Columbus's enterprise was especially important because it was born of an idea — of the hypothesis of the Earth's sphericity. And the navigator's achievement brilliantly confirmed that hypothesis. From acceptance of the Earth's roundness it was but a single step to accepting its rotation about its axis.[12]

[12] This is a rather strange claim in this book. The sphericity of the Earth was well established in the antuquity, but it was not definitely a "single step" as is stated to go to rotate from there. – DM

Yet these assumptions contained other, far more precious seeds. The world was prepared for a transformation of its worldview. That transformation matured within society itself, at its very heart. Only a genius was required to take the final step. Such a genius was the canon of Frombork, Nicolaus Copernicus of Torun. He crossed the Rubicon.

Nicolaus Copernicus was no nihilist. By temperament he was not even a fighter, although his whole life passed in continual struggles — not only in the figurative sense but sometimes in the literal one as well. He was a devout Catholic, a relative of a bishop, and a clergyman by conviction rather than compulsion. Yet in serving God he served, above all, truth. He was not only a genuine scholar but also a deeply honourable man.

How much inner courage this naturally modest and reserved individual must have possessed in order to cast aside the triple fetters of habit, Holy Scripture, and com-

mon sense, and to proclaim his adherence to the "absurd" views of ancient authors who asserted that the Earth rotates around the Sun.

Possessing broad learning in mathematics and philosophy, Copernicus was inclined towards theoretical reasoning. The canon of Frombork[13] justified his model of the universe without recourse to empirical demonstration, proceeding in a purely speculative manner. He wrote:

> "In the midst of all these orbits rests the Sun. For in this most beautiful temple, could this luminous body be placed in any better position from which it might illuminate the whole? Not without reason, therefore, have some called it the soul of the universe, others the ruler of the world. Hermes Trismegistus names it the Visible God, and in the *Electra* of Sophocles it appears as the All-seeing. Thus the Sun, as though seated upon a royal throne, governs the family of stars revolving around it. The Earth is attended by the Moon and, as Aristotle remarks in his treatise *De Animalibus*, the Earth has the closest affinity with the Moon. Yet at the same time the Earth is fertilised by the Sun and carries its fruit for a whole year."

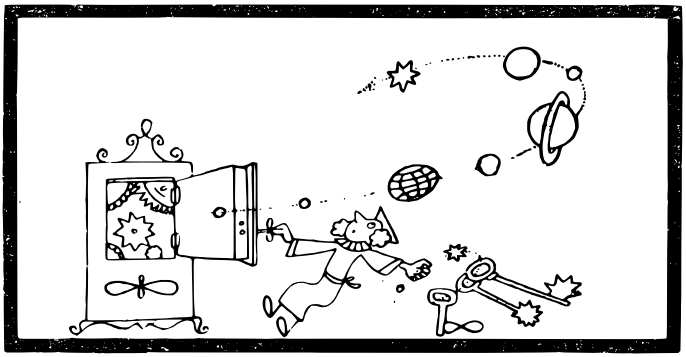
A son of his age, Nicolaus Copernicus felt the beauty and harmony of the world's structure and sought to express it in his model.

In the spirit of the Renaissance, he taught a critical attitude towards the evidence of the senses. Thus, unlike the world-systems of Aristotle or Claudius Ptolemy, the motion of the heavenly bodies in the Copernican system

[13] Canon of Frombork – an ecclesiastical title held by Nicolaus Copernicus at the cathedral chapter in Frombork (then part of Royal Prussia). A canon was a member of the church administration, not necessarily a priest. This position provided Copernicus with income and stability, allowing him to pursue his astronomical work, including the formulation of the heliocentric model. – DM

was relative. One ought not to take the apparent motions of the planets for real ones. Just as it seems to a person that the Earth stands still while the Sun and planets circle around it, so inhabitants of other planets would fall into a similar illusion. They too would suppose that the Earth moves around their motionless world.

This denial of the Earth's immobility later made it possible to assert that the frame of reference for all motion relative to the Earth has *no absolute character* — a conclusion that played a significant role in the formation of a materialist worldview.



Not everyone, and not at once, accepted Copernicus's idea seriously. The objections were substantial. How, for example, could one prove that the vast Earth rotates swiftly on its axis and travels around the Sun? Where, then, is the hurricane wind that should always arise from such rapid motion? Or why does the Earth's rotation not cause a falling

cannonball to deviate?

To answer these serious objections, the world required Galileo Galilei.

For the time being, however, the theory of Nicolaus Copernicus was accepted by most astronomers as an abstraction, convenient for mathematical calculation. To mathematics, what difference does it make whether one assumes the Sun or the Earth to be in motion? But in reality...

Copernicus's system still remained closed, bounded by a sphere of fixed stars. This view was shared not only by the majority of his contemporaries but also by many scholars of the following generations.

The same conception of the universe was held by Johannes Kepler. He even calculated the radius of this "stellar sphere of ice and crystal". It proved to be smaller than Copernicus had supposed, yet still equal to sixty million Earth radii — an astonishing distance for that age. (It may be noted that today this is one hundred times less than the shortest distance to Proxima Centauri, the nearest neighbour of our Sun.)

Attachment to the old model is understandable. Beyond the outer sphere lay the most honoured realm in the entire structure of the universe — the dwelling of the blessed in the system of Aristotle, or the abode of God in that of Claudius Ptolemy. To violate its integrity meant, in effect, to raise one's hand against God Himself. Copernicus

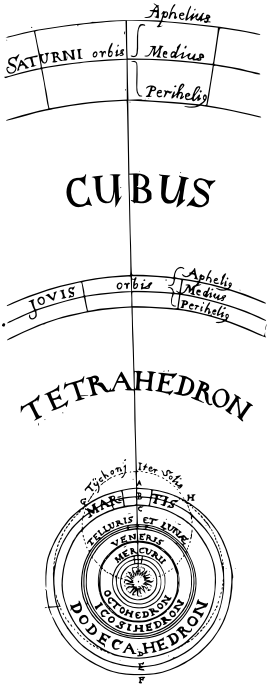
and his follower Kepler were too sincere as Christians to take such a step consciously.

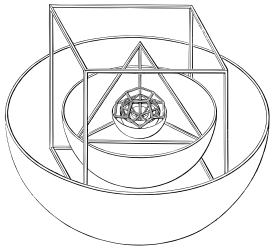
And yet it was through their labours that, together with the crystal spheres, the very heavens in which the angels were firmly enthroned disappeared. The distinction between the earthly and the celestial lost its meaning. Man ceased to be the centre of the universe. Had Copernicus foreseen the consequences to which his teaching would lead, he might have been horrified. The Church awoke to the danger — but too late. The mechanism of history had already been set in motion.

In 1596 the young provincial lecturer in astronomy and mathematics at Graz, Johannes Kepler, published his book *The Mystery of the Universe* (*Mysterium Cosmographicum*). In it he sought to explain the structure of the Copernican system from the standpoint of philosophical harmony.

Kepler linked the distances of the planets from the Sun with the five regular polyhedra known as the Platonic solids. Since antiquity these figures had been endowed with certain mystical properties. Upon each concentric planetary sphere — for at that time it was not yet known that the orbits are ellipses — he inscribed, almost exactly, one of the regular polyhedra in such a way that its vertices touched the next planetary sphere (See the margin figures. – DM). Kepler concluded that this could not be accidental.

The five geometric bodies — the octahedron, icosahedron, dodecahedron, tetrahedron, and cube — placed between the six planetary spheres seemed to him "most





weighty" arguments in favour of the new system.

Yet this treatise had no genuine scientific significance. It is important to us chiefly as evidence of Kepler's firm adherence to the teaching of Nicolaus Copernicus.

Kepler's powerful imagination, inclined towards fantasy and mysticism, was combined in him with scrupulous honesty. Woven of contradictions, he spent his entire life attempting to penetrate the secrets of the universe. Having read one of Kepler's letters, Albert Einstein wrote:

> "We feel in Kepler's letters that we are coming very close to the soul of a deeply sensitive and passionate man. This passion is directed towards the search for the most profound explanation of the processes of nature."

Yet, despite his integrity, his intellectual power, and his inability to compromise, Johannes Kepler was not by temperament a fighter. In order to secure for the new system the right to exist, it required a propagandist and populariser.

3.3 The Immortality of the Great Heretic

On Thursday, 17 February 1600, at two o'clock in the night, the bell of the Confraternity of the Beheading of Saint John the Baptist tolled dully in Rome. Each monastery and brotherhood had its own signal. The ringing from this tower meant that in the morning there would be a burning.

From the church of Saint Ursula the hooded brethren

went to the prison in the Tower of Nona. There, in the chapel, stood the condemned heretic. A requiem was sung. The brothers chanted prayers "for the repose of his soul", urging the prisoner to renounce his obstinacy and sign a recantation.

After the service, the procession with the unrepentant sinner left the prison tower, crossed the bridge, and passed along the narrow streets to the square of Campo de Fiori. There, near a corner house and opposite a stone inscribed with Latin verses in honour of Pope Sixtus IV — who had established upon that square the "throne of divine justice" — the pyre had been prepared...

The torches of the escort crackled. The executioners tore the garments from the condemned man and placed upon his shoulders the *sanbenito* — a coarse shroud painted with tongues of infernal flame and soaked in sulphur. He was fastened to the stake with an iron chain and bound tightly with a wet rope. In the heat the rope would dry, shrink, and cut into his flesh, intensifying his torment — to the greater glory, as they believed, of a merciful Lord.

At his feet were piled his books and those prohibited by the Holy Church which he had read. His tongue was drawn from his mouth and clamped in iron. Then the faggots were set alight.

Through smoke and flame a monk extended a crucifix to the dying man — but he turned his gaze away...

That man was Giordano Bruno.

Thus ended the life of the former Dominican monk Giordano, son of the late Giovanni Bruno of Nola — Giordano Bruno.

In the Eternal City the second day of magnificent jubilee celebrations marking the advent of the new century was under way. Before the Church festivities could begin, praise was to be rendered to God through the holy act of condemning and burning a heretic.

Heretic and atheist, fallen monk, renegade priest, immoral man, rebel against Christ and the Church... revolutionary... philosopher and Master of Arts, a man of phenomenal memory, exceptional ability, and remarkable learning in many branches of knowledge — such were the sharply opposed judgements passed upon Bruno by his enemies and his friends.

What, then, earned him both such deep devotion and such fierce hatred from his contemporaries?

> When freely I unfurled my wings,
> The higher did the wave upbear me,
> The broader blew the wind around me;
> Scorning the vale, I sought the sky.
> The son of Daedalus I shamed not
> By falling; still I mount as high.
> And if I fall, as he did fall,
> No other end would I desire —
> Was it not I who praised bold fire?

So wrote Giordano Bruno in one of his sonnets, expressing in poetic form the programme of his life: to comprehend

the world not as a religious doctrine, but as a captivating and alluring mystery of nature.

"At fourteen or fifteen years of age I entered as a novice the Dominican Order, in the monastery of Saint Dominic in Naples," — so are recorded in the proceedings of the Inquisition the words of Giordano Bruno. "After a year of novitiate I was admitted to the monastic vow..."

Yet this did not mean that from that time Brother Giordano was to devote himself entirely to fasting, prayer, and mortification of the flesh. In the sixteenth century many male monasteries, according to contemporary testimony, resembled veritable dens of disorder. On 13 August 1587 a special decree was even issued: Pope Sixtus V ordered that monks, under no pretext whatever, were to stage comedies, nor were they to admit into their brotherhood thieves, hired assassins, swindlers, or similar characters.

The Dominican Order, however, resisted the prohibition, appealing against it as a violation of the right of sanctuary, and succeeded in having it revoked. Men pursued by the law continued to wander within monasteries in monastic garb. Beneath their habits they wore armour and armed themselves with heavy knives and daggers, setting out on nocturnal adventures — this despite the fact that, under Neapolitan law, the bearing of weapons was punishable by death.

There were also many disputes within the monastery walls concerning the dogmas of Holy Scripture, the rites and ceremonies of worship, and especially the widespread

Italian veneration of various fetishes — crosses, statues, figurines, and icons. Many humanists spoke out against such "papist idolatry".

Giordano was only eighteen when, after one such dispute with his brethren, he cast the images of the saints out of his cell. From that moment, it seems, began the turning point in his outlook — a turning that would lead him towards complete atheism.

Bruno came to hate his Order, to hate monasticism as such, and the entire clergy, including the Pope himself. "Whoever utters the word 'monk', " he wrote, "thereby signifies superstition, the embodiment of avarice and greed, the incarnation of hypocrisy, as it were the sum of all vices. If you wish to express all this in a single word, say: 'monk'."

Giordano Bruno was poor. He had neither patrons nor the means to purchase books, nor even a safe place in which to keep them. Monastic cells were frequently searched, and monks were forbidden to read secular literature. There was only one solution: having obtained a necessary book, the young Nolan committed what he required to memory. At the same time he strengthened his natural powers of recollection, training them according to the method of the medieval Spanish philosopher Ramon Llull.

During eleven years in the Dominican monastery Bruno passed through all stages of study and received the degree of Doctor of Theology. Soon afterwards, however, he was summoned to Rome upon denunciation, accused

of heresy. Then Bruno "abandoned the clerical state, laid aside the monastic habit, and departed".

Thus began his wanderings — first through Italy, then through Switzerland and England. The learned master wrote prolifically, denouncing the dullness of Catholic clergy, the greed and corruption of popes, and the absurdity of Catholic religion as such. He published his works with the aid of friends in clandestine presses or anonymously. He lectured in the higher schools of France — at Lyon and Toulouse, and in Paris — attracting large numbers of Protestant students.

In England, at Oxford, he took part in a celebrated disputation with doctors of theology, brilliantly defending his new conception of the world as set forth in his books *The Ash Wednesday Supper* and *On the Infinity, the Universe and Worlds*.

The official documents describing this event do not name the precise subject of the debate. Yet from Bruno's own words it is clear that he defended above all the correctness of the theory of Nicolaus Copernicus, at that time known only to a few. He argued that our world is but a negligible part of the universe, that there exist countless other inhabited worlds, and that the stars are distant Suns around which other Earths revolve.

Giordano Bruno was among those who raised high the name of Nicolaus Copernicus and compelled others to think about his theory and to dispute it. The Oxford debate forced him to leave England. He moved to Germany,

continuing to develop his idea of the spatial infinity of the universe.

For this conception he had no need of God.

> "Neither the heavenly bodies nor our planet are fixed and immutable — worlds continually arise and perish; over immense stretches of time the face of the Earth changes, seas become continents, and continents seas."

The notion of an infinite universe and of countless inhabited worlds had indeed been advanced before. Yet such hypotheses had perished as brief heresies. Bruno's cosmology remained in the history of science because its author rested upon the new teaching of Copernicus and carried its philosophical implications further.

> "It is impossible for a rational and living mind to imagine that all these innumerable worlds, as magnificent as ours or even more so, should be deprived of inhabitants like ourselves or even superior to us."

Germany followed Germany: Mainz, Wiesbaden, Marburg, the university town of Wittenberg — stronghold of Lutheranism; then Prague, Helmstedt, Frankfurt am Main. In 1589 the Protestant superintendent of Helmstedt, Gilbert Voetius, excommunicated Bruno, pronouncing the customary formula:

> "Beloved brethren in Christ! Giordano of Nola has long persisted in the sin of blasphemy. Repeated exhortations by the Word of God and punishments imposed by the secular authority have not led him to Christian piety. Lest the diseased sheep infect the whole flock of the Lord, lest his scandalous example

harm the entire Christian community..."

And so forth.

The Lutheran Evangelical Church differed little in practice from the Catholic. Once excommunicated, Giordano Bruno was deprived of all participation in public life, save for commercial dealings. He was forbidden almost everything. During divine service he was to be led into the church in an iron collar and chain, like a wild beast, brought to the centre, and made to kneel.

Having barely gathered the necessary funds, Bruno and his pupil Hieronymus Besler departed for Frankfurt. The city refused him the rights of citizenship and residence. "His petition must be rejected," wrote the burgomaster upon Bruno's request, "and let him be told that he may spend his coins elsewhere." Expelled from Frankfurt — where his books were being printed — he moved on to Zurich.

In 1590 Pope Sixtus V died, allegedly poisoned by enemies. A storm that broke out on the night of his death gave rise to a legend that the devil himself had come to claim the Pope's soul. That same year Bruno, accompanying booksellers, crossed the frontier of the Venetian territories by mountain paths, returning to Italy.

Thus was nearly completed the life journey of the bold Nolan, the uncompromising atheist and advocate of new ideas. What followed was grimly predictable. A provocateur presented himself as a friend. On the night of 22–23

May 1592 Bruno was treacherously arrested by the very man who had lured him into his house. Within a day he was in the prison of the Venetian Inquisition.

Eight years in dungeons. Eight years of interrogations. The ritual of excommunication and curse did not break the spirit of the Great Heretic. Faithful to his teaching and to his convictions, he mounted the pyre at Campo de' Fiori — the Field of Flowers — and, in ending his life, attained immortality.

Let us bow our heads before his courage, and hope that in a difficult hour we too may possess the strength to stand by the ideals we profess.

3.4 *Eppur si muove!*

Galileo Galilei was the son of Vincenzo Galilei, a well-known disputant, musician, and philosopher in Pisa. The son inherited his father's temperament and in youth dreamed of becoming a painter. Yet painters in Italy were abundant, as were musicians and philosophers. Good physicians, however, were fewer — and mankind has always retained the unfortunate habit of falling ill. When they are ill, not only their spirits weaken, but also the strings of their purses. In short, Vincenzo Galilei sent his son to the university to study medicine.

Perhaps he might have become another obscure follower of Hippocrates, had not the student Galileo one day

— whether by mistaking lecture rooms or simply out of curiosity — wandered into a lecture on the geometry of Euclid. Struck by the order and logic of the teaching, the young man "fell ill" with mathematics instead.

The sixteenth-century student's timetable was not so burdened as that of the twentieth century. Galileo found ample time to acquaint himself thoroughly with the works of ancient mathematicians and mechanicians. And when, during divine service, observing a swinging lamp, he suddenly grasped the law of the pendulum's oscillation, Asclepius lost him for ever from the ranks of his followers.

When Galileo Galilei reached the age of twenty-five, one of the many members of the Cosimo I de' Medici family secured for him a post as lecturer in mathematics. The young graduate gladly set about studying the works of the ancients more deeply, interpreting them after the manner of his professors, though for a more modest reward. Had he continued along this well-trodden path, we might not know his name today, for there would have been no scientist Galileo Galilei in history.

Yet one day he conceived the idea of testing one of Aristotle's assertions by experiment — a thought which, for that time, bordered on madness. Naturally, Galileo discovered an error. The discovery gave him immense satisfaction. There were, in truth, no shortage of errors in Aristotle's views, and Galileo resolved to correct them.

With that decision the scientist was born within him — a man who placed service to truth above all else. A sci-

entist is not a post, nor even a title; it is a vocation. It is not necessarily a glamorous occupation to wrestle with intricate problems, and not everyone who devotes his life selflessly to science becomes a Galileo — especially in an age when science is so profoundly collective. Yet for one who is a scientist by calling, no other life is conceivable.

Galileo felt genuine delight each time he succeeded, after analysing some established doctrine, in proving it mistaken and in discovering the true relations "between things". When he exposed an error in Aristotle or in one of the Peripatetics, he readily shared his findings and defended his position with remarkable ardour.

In disputation he knew no fatigue. He overcame his opponents with such wit and cogency that soon in neither Pisa nor Padua — to which he had moved owing to the difficult situation created by his "well-meaning colleagues" — were there rivals left to challenge him. Such renown, however, brought him few friends. The young Galileo burned with ideas that consumed him. Not only did he, like Johannes Kepler, long to uncover the truth about the world at any cost; he also yearned to proclaim it to others.

Every investigation, every inquiry, the professor of Padua conducted by means of his own experimental–mathematical method. Each conclusion had to rest upon propositions already demonstrated. Today such a principle may appear elementary. Yet more than three centuries ago it was a revelation. In truth, with Galileo Galilei real physics began to develop.

He elaborated a new approach — the method of experimental natural science. From observed facts Galileo moved to the idealisation of a phenomenon, and only then, through an ideal model, to theory. In effect, he provided the modern methodology of empirical science, constructing an entire set of conceptual models upon which Isaac Newton would later build. Through them Newton arrived at many of his discoveries, which became the foundation of the modern picture of the world.

Brilliantly conceived experiments combined with remarkable intuition distinguished Galileo from his predecessors. One might suppose that by dropping wooden and iron balls from the Leaning Tower of Pisa anyone would have been convinced that all bodies, regardless of their weight, fall with the same acceleration. By no means.

First, Aristotle had asserted the contrary; and secondly, the experimental result was far from so obvious that a law could simply be written down from it. It required a powerful imagination — one had to be Galileo.

Even keener foresight was needed to formulate the principle of inertia. Here too he had to stand against authority, to demonstrate a new and unseen property of bodies: that they preserve a state of rest or of uniform straight-line motion until some applied force alters that state.

Having become acquainted with the astronomy of Nicolaus Copernicus, Galileo Galilei became its ardent champion. In those years the system of the canon of Frombork urgently required popular defence. It diverged so sharply

from the accepted science of the time, and possessed not a single clearly demonstrative proof, that even progressive thinkers hesitated to take it seriously.

Galileo's lectures drew vast audiences. From nearby Venice many noblemen travelled to Padua to hear his reflections on heliocentrism. When the largest lecture hall of the University proved too small, he continued under the open sky. With what fearless conviction he spoke — and courage was indeed required.

As early as 1597 he wrote in a letter to Johannes Kepler:

> "I came to the opinion of Copernicus many years ago, and from it I have discovered the causes of many natural phenomena that are utterly inexplicable by the common hypotheses. I have written many considerations and refutations of opposing arguments; yet I have not dared to publish them, deterred by the fate of our teacher Copernicus. To a few he has earned immortal glory, and by countless numbers — for such is the multitude of fools — he has been mocked and derided..."

He understood clearly that to challenge established cosmology was not merely an intellectual act but a public risk. The question was not simply whether the Earth moved, but whether authority itself could be questioned. And that, perhaps, was the more dangerous proposition.

From year to year Galileo Galilei spoke with increasing fervour and with diminishing caution. The number of his enemies grew accordingly.

Meanwhile, the salary of a professor of mathematics left much to be desired. Galileo was no longer young. In 1604, when a new star flared up in the constellation Ophiuchus, he was forty years of age. He was no longer merely a "shouter and polemicist" attacking "paper philosophers". By then he had produced detailed investigations of machines, proceeding from a general principle of equilibrium corresponding to the principle of virtual displacements. He had written on the laws of free fall, on motion along an inclined plane, and on projectiles launched at an angle to the horizon. He conducted important studies on the strength of materials. Researched, written, discovered — much had been accomplished.

Yet the inquisitive reader would search in vain through the archives for works published during this fortunate Paduan period. Knowledge of Galileo's serious and painstaking scientific labour was confined largely to a small circle of friends. This was not due to excessive modesty. Rather, he regarded most of his studies in dynamics as unfinished.

Galileo has had many biographers. One must confess that earlier the image of the scientist did not inspire particular sympathy. Youth is often severe and uncompromising in its judgements. The official title, instilled from schooldays, of "martyr of science", which so often accompanied Galileo's name, seemed incompatible with the recantation and repentance of the ageing professor summoned before the Inquisition in Rome. A youthful spirit might demand of a "martyr" death for an idea in the flames of a pyre rather than submission.

Time, and a closer acquaintance with Galileo as a man, are required to overcome such a judgement.

In 1609 Galileo Galilei was a tall, powerfully built man of forty-five, in excellent health, with bright eyes and a magnificent reddish beard. Nor did he devote himself solely to science. His official teaching load amounted to no more than one hour a week — leaving ample time for other pursuits.

He was not indifferent to worldly pleasures. He enjoyed good food, did not refuse a cup of wine, dressed with taste, and — pious moralists may look away — had three children, though he was never formally married. Galileo appreciated success, and much of it fell to this vigorous and cheerful man. If on occasion he boasted a little — well, he had something to boast of, and he was, after all, an Italian.

In that same year he learned, from a letter written by the French envoy, of a remarkable device invented in the distant northern Netherlands — an instrument capable of bringing distant objects nearer. The letter even contained a description of it, recorded "from the words of an eyewitness". One may ask: how reliable is an eyewitness account when one attempts to reconstruct a mechanism from it?

To construct a telescope on the basis of such a description was hardly easier than understanding the workings of a complex machine from its manual. Yet not every reader of instructions is Galileo. The professor of Padua ground lenses in his own workshop and assembled from them a spyglass that magnified objects threefold.

"A mere opera glass," an experienced reader might remark — and not without reason, for the image quality of a modern theatre binocular surpasses Galileo's instrument a hundredfold. The difference lay elsewhere: the professor had constructed the first telescope in Italy, and to the citizens of Padua it seemed a marvel. When Galileo Galilei climbed a tower to admire the view through his "remarkable device", a queue formed at the little eyepiece as eagerly as crowds gather for a new spectacle in any age.

A messenger from the Venetian Council arrived and hinted, with diplomatic clarity, that the Council would not object to acquiring such an instrument. Galileo, with a grand gesture, presented his telescope to the envoy, observing that the "invention" had cost him much labour and that he had derived it himself from the secret rules of perspective. One may question his complete sincerity. Yet a certain inclination to boastfulness was common — and seldom condemned — in the confident atmosphere of the Renaissance. A modest salary may also have played its part.

Galileo's second telescope magnified eightfold. Then he conceived a brilliant idea: to turn the instrument towards the heavens. What he saw was astonishing. According to Aristotle, the Moon ought to have been a smooth sphere; instead it appeared scarred with craters and broken by mountains. Venus displayed phases like those of the Moon — evidence that its orbit lay closer to the Sun than the Earth's path, thus supporting the theory of Nicolaus Copernicus.

Finally, the Milky Way resolved itself into myriads of stars, overturning the notion that it was a mere nebulous substance.

At last the spheres of Aristotle, which had enclosed the world, burst like rotten shells, opening before mankind the immensity of the universe.

Yet mankind, clinging to its saving conservatism, was in no haste to look through a telescope at the stars. When the cheerful, red-bearded giant, Galileo Galilei, invited his learned colleagues to verify his claims, many — perhaps the more prudent — declined. Those unable to resist temptation glanced with one eye, recoiled, crossed themselves, and withdrew thoughtfully, casting cautious looks towards the building where the Congregation of the Holy Inquisition customarily assembled.

He wrote to Johannes Kepler:

> "Let us laugh, my Kepler, at the great folly of mankind. What shall one say of the foremost philosophers of this academy, who, with the obstinacy of an adder, despite a thousand invitations, have refused even to look at the planets, the Moon, or the telescope? Truly, as he who has no ears does not hear, so these men have their eyes closed to the light of truth. It is remarkable, yet it does not astonish me. This sort of people imagine that philosophy is some book, like the *Aeneid* or the *Odyssey*, and that truth is to be sought not in the world, not in nature, but in the comparison of texts. Why should I not laugh with you? How heartily you would laugh if you heard what the

> chief scholar of this academy argued against me before the Grand Duke of Tuscany — how he strove, by logical arguments as by magical incantations, to call back and banish the new planets from the heavens..."

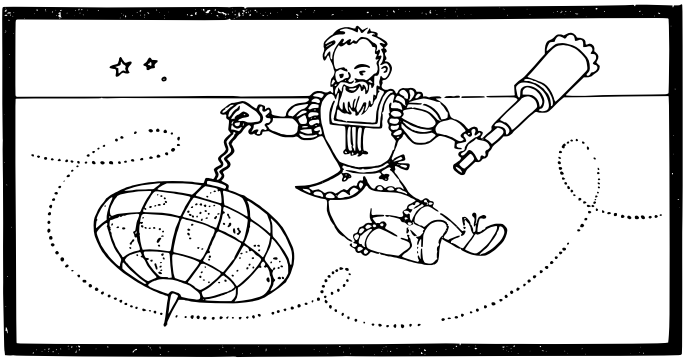
The dispute was no longer merely astronomical. It had become a struggle over where truth was to be sought — in inherited authority, or in nature itself.

With a telescope magnifying thirtyfold, Galileo Galilei discovered the satellites of Jupiter — four small stars revolving about the planet in the same manner as the planets revolve about the Sun. For the first time mankind could observe, as it were, a visible model of the system of Nicolaus Copernicus.

Galileo attempted at first to "sell" the titles of the new stars to the King of France, and later to the Pope. Both appear to have declined such costly celestial honours. Weary of universities, lectures, students lodged in his house, and the stifling and petty atmosphere of Padua — and not least of the long academic robes he mocked in satirical verses — he resolved to return to his native Tuscany.

He moved first to Pisa and then to Florence, accepting the title of "First Philosopher and Mathematician" to the Most Serene Grand Duke of Tuscany, Cosimo II de Medici. Preparing to leave Padua for service at the Florentine court, Galileo finally named the satellites of Jupiter the Medicean Stars. Whether this alone secured his advancement is difficult to say.

He promised the Duke much: two books on the system of the universe; a vast work embracing philosophy, astronomy, and geometry; three books on motion, three on statics, two on the demonstration of principles, one on problems; treatises on sound and speech, on light and colour, on tides, on the composition of unusual magnitudes (that is, on what would later become differential calculus, independently developed a century afterwards by Gottfried Wilhelm Leibniz and Isaac Newton), on the motion of animals, and even on the art of war.



His interests were indeed wide-ranging. Yet to realise such ambitious plans he required tranquillity, leisure, the protection of a powerful patron, and a generous salary.

Cosimo II de' Medici received his First Philosopher and Mathematician with a cascade of favours. Galileo Galilei was presented with a golden chain as a mark of distinction and granted almost everything he had requested. His pop-

ularity reached its height. Courtiers read his works with enthusiasm; Federico Cesi, founder of the Accademia dei Lincei, elected him a member. Even the General Inquisitor, Cardinal Robert Bellarmine — and the future Pope Pope Urban VIII — regarded him favourably. Pope Pope Paul V himself listened to him with evident interest. His position seemed enviable.

Yet envy, that unworthy companion of fame, soon appeared. It grows in proportion to success. In these very years a secret dossier on Galileo was opened in the offices of the Inquisition. Priests began attacking him in their sermons, openly declaring his defence of the Copernican doctrine heresy. Galileo responded sharply, advancing arguments he deemed unassailable in support of the new system of the world. He composed public letters comparing Holy Scripture and science. "The Holy Spirit teaches us how to go to heaven, not how the heavens go," he declared, confident in the backing of powerful patrons.

In 1632 there appeared in Florence his book *Dialogue Concerning the Two Chief World Systems* — formally titled *Dialogue of Galileo Galilei, Member of the Academy of the Lincei, Extraordinary Mathematician of the University of Pisa and First Philosopher and Mathematician to the Most Serene Grand Duke of Tuscany, in which, in conversations over four days, discussion is held concerning the two principal world systems, Ptolemaic and Copernican, and inconclusive philosophical and physical arguments are advanced on both sides*.

The work contained a critique of the Peripatetic doctrine that the universe consisted of two fundamentally different substances — the elemental, terrestrial matter and the celestial — and that these differed in their very nature.

Written both in Latin, for the learned, and in Italian, for a wider readership, the *Dialogue* opened — from its very preface — with a pointed thrust against the Inquisition. Its pages were filled with detailed, popular, and often brilliantly witty arguments explaining the system of Nicolaus Copernicus. If Copernicus's own book had been understood by few, Galileo's exposition proved a revelation.

His opponents persuaded Pope Urban VIII that, under the guise of the simple-minded Peripatetic Simplicio, Galileo Galilei had caricatured the Pope himself — the Christian shepherd and successor of the Apostle Paul. Urban took offence. The book was confiscated, and the seventy-year-old Galileo was summoned to Rome. The trial began.

On 22 June 1633 it ended. Galileo was required to sign a recantation "of his heretical doctrine". He was to express repentance and promise humbly "to inform the Inquisition of all who might follow it". He heard the sentence of lifelong imprisonment.

People are reluctant to relinquish the noble images they cherish of their heroes. Hence the enduring legend that, rising from his knees in the church of Santa Maria sopra Minerva, Galileo stamped his foot and cried, "*Eppur*

si muove!" — "And yet it moves!" There is even a painting depicting the proud old scientist confounding the prelates with these words. Yet this is only a legend.

The aged and infirm Galileo was no longer fit for open struggle. Time had broken his strength. He did not, like Giordano Bruno, confront his judges with defiance. Instead, he bowed — and lived on under sentence, while the Earth continued its motion regardless.

No, Galileo Galilei did not utter proud and defiant words before an unjust tribunal. In the phrase of Bertrand Russell, "it was not Galileo who spoke them, but the whole world."

Did the Church succeed, by that ignoble spectacle, in breaking the scientist's spirit? Galileo lived for nine years after the trial — living as a "prisoner of the Inquisition", forbidden to discuss the motion of the Earth, forbidden to publish anything at all. His health declined. Yet his mind remained "too alive for so feeble a body".

He began work on a major book, *Discourses and Mathematical Demonstrations Relating to Two New Sciences*. It was a profound summation of his physical investigations — of accelerated motion, of elasticity, and of the foundations of the calculus of infinitesimals.

Age intervened. Galileo lost his sight — first in one eye, then in the other.

> "Alas! Your faithful friend and servant is completely and irreparably blind. These heavens, this Earth, this universe, which I, contrary to the notions of

> former ages, enlarged a thousandfold by my observations, have now shrunk for me into the narrow space which I myself occupy,"

he dictated sorrowfully to his pupil Vincenzo Viviani.

On 8 January 1642 the great scientist died. At his deathbed stood his son Vincenzo, his daughter-in-law, two pupils — Viviani and Evangelista Torricelli — the local priest, and two permanent representatives of the Inquisition.

Even blind, even having recanted, he remained formidable to the Church. The fathers understood that, despite outward submission, the spirit of the great scientist — and of the great heretic — had not been broken.

3.5 René Descartes (Cartesius)

If Nicolaus Copernicus laid the foundations of a new picture of the world, and if Galileo Galilei created mechanics as a doctrine of motion and equilibrium within that world, then René Descartes established a conception of the universe as an immense machine — once set in motion by God and thereafter continuing to operate according to mechanical laws without further divine intervention.

Born into an old French family, Descartes began his education at a Jesuit college. On completing his studies, in accordance with custom, he entered military service. At sixteen he was already an officer, living the somewhat scattered life typical of the young men of his time.

At the age of thirty-three he left the army and, without leaving an address, withdrew to the quiet of the Netherlands. There he led a secluded life, studying the philosophy of the ancients and reflecting deeply. He set himself the task of constructing a new and independent view of science and its method.

Descartes was convinced of the primacy of intuition. He held that the general laws of nature could be established through logic and mathematics. Experience he relegated to a secondary role, regarding it as an auxiliary instrument of deductive thought.

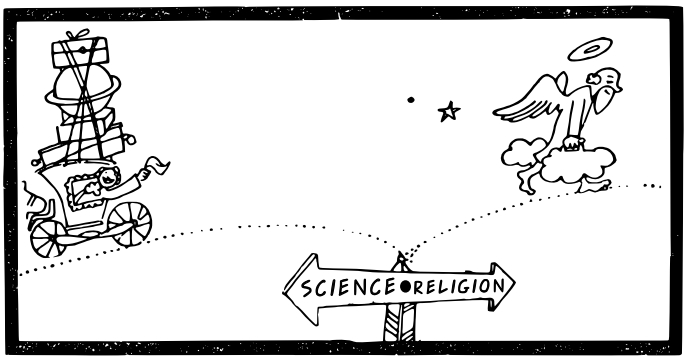
One may ask whether such confidence in pure reason risks detachment from the stubborn facts of nature. Yet for Descartes, certainty was to be sought first in clarity of thought, and only then in observation.

René Descartes possessed a brilliant command of mathematics. Before him, geometry had served chiefly as a means of studying Euclidean space and the figures within it, while Babylonian–Indian–Arabic algebra existed as a largely separate discipline. Descartes united them in what became *analytic geometry*. He introduced into practice the system of rectangular coordinates, x and y, making it possible to express curves by algebraic equations. In doing so, he prepared the ground for the later creation of differential calculus.

Rejecting the views of classical philosophy, he arrived at the idea of two distinct realms: the world of matter, whose only truly real properties are extension and motion;

and the world of soul and mind. Matter, in his conception, was inert and unanimated, capable only of mechanically transmitting motion through contact with other matter. The initial impulse — the first act of animation — had to be given by God. Descartes had no wish to quarrel with the Church and therefore ensured that his system, no less than that of Aristotle, affirmed the existence of God.

Walking along the quiet canals of the Netherlands, he observed the flow of water, swirling into small vortices near the dams, drawing leaves and blades of grass downwards. "Might not the world have formed in such a way?" he wondered. God created matter from nothing and imparted to it an initial motion — but thereafter?



From this reflection emerged his celebrated vortex theory. Boundless space, filled with matter and invisible ether, was at first in complete chaos. Then vortices arose. Like vast centrifuges, they sorted matter: larger particles gath-

ered with larger, smaller with smaller. From the coarser aggregations planets and comets were formed; from finer, mutually smoothed particles — liquids and the heavens; from the finest — the Sun and the stars.

The universe, in this vision, became a grand mechanical process. Yet one may question whether such elegant symmetry reflects nature itself — or the order imposed upon it by a powerful mathematical imagination.

Vortices, vortices — was it not from them, Descartes reasoned, that the planets move in closed paths about a central luminary? In his vortex scheme there was no room for a God who constantly intervened. The world-picture appeared clear after the tangled explanations of the Peripatetics and, at the same time, sufficiently guarded against theological attack. It therefore spread widely.

However much René Descartes withdrew from society, frequently changing his residence and corresponding chiefly with Marin Mersenne — the so-called "postbox of European science" — he could not disappear from the sight of the Church. It was fortunate that he had chosen Protestant Holland. In Catholic France his position would long since have become dangerous. As his fame grew, Protestant pastors also began accusing him of atheism. The philosopher was alarmed. The embers of the fires that consumed Michael Servetus and Giordano Bruno were not yet cold; the mother of Johannes Kepler had been condemned as a witch; Galileo Galilei had been summoned to Rome before the Inquisition.

Descartes was preparing to send his *Discourse on the Method* to Father Mersenne when news reached him of Galileo's condemnation and recantation.

> "This so shocked me that I was almost resolved to burn all my papers, or at least to let no one see them;... I confess that if the motion of the Earth is false, then all the foundations of my philosophy are false as well, for they clearly lead to the same conclusion,"

he wrote. Only four years later did the work appear in Dutch publishing houses, setting forth the essence of his views.

If one were to summarise, boldly and succinctly, what Descartes urged, it might be put thus: doubt. Doubt, rather than accept the word of authority. Think for yourself. A person may rely only on the powers of his own reason. And further: in order to discover truth, one must once in one's life subject everything to doubt, so far as that is possible.

Yet even here a question arises. If all is doubted, what remains certain? Descartes' answer would be stark: *the very act of thinking*. From doubt itself he would extract his famous certainty — that *the thinking self exists*.

The ideas of René Descartes spread so rapidly through the universities of the Netherlands that Protestant professors grew indignant. The chief pastor in Utrecht, Gisbertus Voetius — a name already encountered in connection with Giordano Bruno — even built his career on persecuting

philosophers. As a professor of Utrecht University, combining the enlightenment of minds with service to God, he organised noisy demonstrations against Cartesian views: processions of students shouting, whistling, and applauding in the manner by which unsuccessful actors were once driven from the stage.

Having become rector of the university, Voetius secured Descartes' summons to court. Bells rang in Utrecht; the printed text of the summons was proclaimed by heralds and posted upon house walls. Descartes did not appear. Voetius, however, was satisfied. He prepared to condemn the philosopher in absentia — to exile from the province, to a fine — and was already collecting Descartes' books for burning.

Descartes was forced to seek protection from influential figures. "I am assured," he wrote to the Prince of Orange, "that Voetius has even entered into negotiations with the executioner, that he might make the bonfire as large as possible, so that the flames may be seen from afar..." Intervention by dignitaries ended the farce.

Descartes had no wish for open conflict with religion. His method of smoothing the sharp edges where Scripture was concerned was notably subtle. Scripture teaches that God created the world; Descartes did not dispute this. Yet, he maintained, once the act of creation had been accomplished, the Lord withdrew and no longer intervened in the self-transforming processes of nature.

Thus Descartes made one of the earliest systematic at-

tempts to separate science from religion. From that point onward, inquiry might proceed without direct fear of ecclesiastical interference — provided theological doctrines were not openly challenged.

Peace in Holland did not last. Descartes accepted an invitation from Queen Christina of Sweden to come to Sweden. The severe northern climate proved ill-suited to his fragile health. He caught a chill, developed pneumonia, and died in his fifty-fourth year.

One may wonder whether the life of a thinker devoted to doubt and reason was not itself shaped, at every turn, by the very authorities he sought to transcend.

The cosmological ideas of René Descartes — or Cartesius, as he signed his works in Latin fashion — are today largely forgotten. Despite their mathematical dress and appeal to observation, his system was little more than a vision, almost a "myth of what the new science might become". Yet it helped to displace the worn-out structure of medieval scholasticism from the universities of Europe.

Descartes was among the first to assert that the laws of nature are valid because they were established by God. This view long dominated the minds of scholars in many lands. It was shared by Isaac Newton and his contemporaries, who believed they were uncovering the great laws ordained by the Creator but not yet discovered by men.

Descartes spoke of the development of the universe. In doing so, he opposed the centuries-old metaphysical

tradition which had insisted upon the constancy and immutability of nature "from creation to the Last Judgement". In fact, he was among the first since Democritus to attempt to consider not only the structure of the world, but its evolution.

In time, the science concerned with the origin and development of individual celestial bodies would be called *cosmogony*. At first, attention would turn to the Earth; then to the Sun and its system; later to other stars — double and triple systems, clusters, and finally to galaxies, vast archipelagos of stars like the Milky Way. Theories and hypotheses would become steps upon a long staircase leading to the firmly closed door of nature's temple — a door towards which we too strive, behind which lies not merely a fragment of the universe, but the whole of it.

From this aspiration would arise *cosmology* — the science of the universe as a whole. And one should not forget that among the first to glimpse that distant door was René Descartes, of whom it was said that he "rebuilt philosophy from its foundations and opened to mortals a new, sure and steadfast path — leaving only one thing uncertain: whether he possessed greater modesty or greater knowledge."

These words are engraved upon his tomb. One might pause there for a moment — and reflect on how often bold imagination precedes firm discovery, and how fragile the boundary is between vision and science...

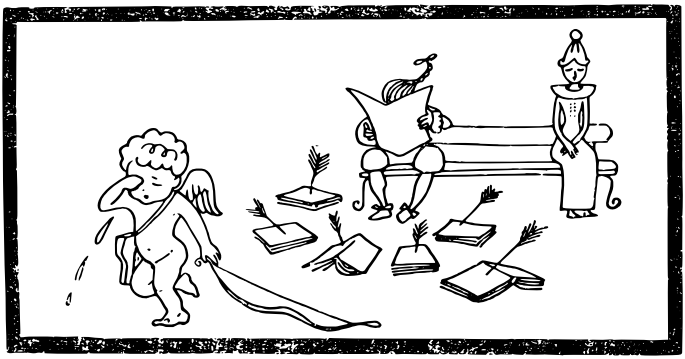
3.6 Isaac Newton

Newton was born a year after Galileo's death and a hundred years after Copernicus had passed. On the day of his birth, 5 January 1643, Descartes was forty-seven years old, residing in Holland, his fame echoing across Europe. Newton's birth passed almost unnoticed. Firstly, it took place in the small village of Woolsthorpe; secondly, it brought little joy to those nearby. His father, also named Isaac Newton, had died before his son's birth, leaving a young widow with very limited means. The times were troubled. The "Ironsides" — so called, the peasant soldiers who rallied under Cromwell to the parliamentary army — fought in the name of future progress, against the Cavaliers, loyal defenders of old feudal order and King Charles I.

By the time the bourgeois revolution triumphed, Isaac was six. He rejoiced with his grandmother, who had raised him, at the dissolution of the House of Lords, though he did not yet understand why this should be a cause for celebration. He also mourned the execution of the king, without yet grasping why Charles I was somehow dear to him.

Six years later, after finishing the village school, Newton was sent to the nearby town of Grantham to attend the school of Henry Stokes. At first, he struggled. Physically weak and awkward, Isaac was a constant target for other boys. He avoided their games, took no part in pranks, and could neither fight nor defend himself — a bitter blow to

his pride. Gradually, he concluded that if not by strength, then by success in study he might improve his standing among peers. Pride, combined with repeated struggles, did its work. Eventually, he became the top pupil, freeing himself from the humiliating role of scapegoat.



Newton had always loved to draw, but now he devoted more time to reading and observing the natural world. Exceptional diligence, along with exposure to the philosophical principles of Bacon and Descartes as taught by Stokes, urged him to test his own ideas experimentally. At sixteen, he undertook his first experiment: to measure the force of the wind, the youth ran against and with it, then carefully measured the length of his leaps...

After Isaac's mother, widowed a second time, decided to withdraw him from school to help with the farm, the boy returned to Woolsthorpe. Having packed his modest belongings and given away his drawings, Isaac bade

farewell to a young daughter of the local apothecary, to whom he seems to have felt a certain affection. On the farm, however, he proved little help. He preferred books to the spade, and solving mathematical problems took him far from counting the farm's profits.

Around the same time, after Cromwell's death, the reaction began. The Republic was abolished. The two-chambered Parliament, consisting of the House of Lords and the House of Commons, eager for a monarch, summoned Charles II, son of the executed king. England, however, had never been lucky with its kings. Charles II flirted with the Puritans while secretly favouring Catholics. He preferred the laboratory to the council chamber, spending his time on scientific pursuits. "As the priest, so the parish," as the Russian proverb goes — fitting even for an English king. Lord Keeper Guilford became absorbed in making barometers; the king's first minister, Buckingham, turned away from politics and intrigue to amuse himself with chemical experiments. Aristocrats polished lenses... Science had become a fashion.

It is believed that Newton's former teacher, Henry Stokes, persuaded his mother to allow him to return to school to prepare for university. His uncle, the Reverend Ayscough, a member of one of the colleges, also played a significant role. In any case, in 1661, a notable year for English science, Isaac Newton entered Trinity College, Cambridge. That same year saw the founding of the Royal Society of London, uniting a group of enthusiasts of natural philosophy.

Already in his first years at university, Isaac Newton, a diligent and orderly subsizer — as impoverished students studying for free were called — quickly became a person of exceptional independent thought. He devoted himself to mathematics, studied optics, and observed celestial bodies. Accustomed to a modest life, Isaac only occasionally allowed himself participation in student feasts or a game of cards... Some biographers even reproach him for stinginess, puzzled by his complete indifference to young women... However, the young man early decided to devote himself to an academic career. According to surviving medieval traditions, college members were required to remain unmarried. Thus, Newton freed himself for life both from romantic dreams and matrimonial aspirations, gaining a wealth of time and undiverted energy for his future debates.

In 1664, a plague epidemic broke out in London. All who could fled the city to escape the disease. Newton too went to quiet Woolsthorpe. The plague of 1664 was a great disaster for England, but how different might history have been had Newton not had this forced two-year "creative leave"... It was there, in the rural seclusion, that the young philosopher conceived and developed all the ideas that had occurred to him at Trinity College. In Woolsthorpe he created his famous analysis of the infinitely small, which he called the "method of fluxions". Today, using Leibniz's terminology, we call this mathematical apparatus differential calculus. Later, when Newton was already an established scientist, a long dispute arose between him and Leibniz,

full of sharp words, reproaches, and mutual insults over priority in developing this method. But that was later, in London. For now, Newton was full of ideas.

He experimented with optical instruments, polished lenses and mirrors. Here he laid the foundations of his views on the nature of light. It was also in Woolsthorpe that Newton first began thinking about the problem of universal gravitation — ideas that would later culminate in his remarkable work, *Mathematical Principles of Natural Philosophy*. Academician S. Vavilov wrote in his biography of Isaac Newton:

> "During the plague years in Woolsthorpe, Newton created the programme of all his subsequent principal scientific work and in large measure carried it out."

3.7 How Useful It Is When There Are No Great Discoveries

Between the publication of Galileo's *Dialogue* and Newton's *Principia* a little more than half a century passed. During this time, astronomy produced no particularly significant discoveries. Yet it was precisely in this period that the old, outdated Aristotelian view of the world — closed within a shell of spheres, shattered by Copernicus, Bruno, and Galileo — died finally, quietly, and irrevocably.

The curious reader may ask: "why does the finale of this long battle of ideas fall on such a seemingly dull time?"

But, as the philosopher Hegel rightly wrote, the happiest times are those about which history textbooks do not write. Let us try to understand. First of all, through the efforts of Kepler and Galileo, Descartes, Bacon, and many others, by this period the Copernican system had ceased to be a sensation. Passions had calmed. The scandalous atmosphere had dissipated. Even the holy Catholic Church quietly began to make use of the God-defying theory to determine the dates of church holidays and to adjust the calendar. The Copernican system became a working scientific hypothesis, spreading into all countries.

In 1657, the scholar, hieromonk, philologist, and preacher Epiphanius Slavinetsky, "an elegant teacher in philosophy and theology, most skilled in Greek and Slavic dialects," was summoned from Kyiv to Moscow for "rhetorical instruction" and the translation of Greek books. Records indicate that among the divine writings, the hieromonk translated into Russian a six-volume work by the Dutch mathematician and astronomer Johan Blaeu, presenting the Copernican system. This was the first, though not entirely reliable, evidence of the new worldview reaching Russia. The translator called his work *The Spectacle of the Universe* — "spectacle" here meaning "overview." The manuscript never saw the light of day. Perhaps the clergyman himself was frightened by the ideas it contained, or perhaps timely advice came from well-meaning members of the clergy. Nevertheless, it was the first glimpse of the approaching dawn for Russia, awakening after the many years of the Tatar-Mongol yoke.

Equally important is that, wearied by general speculation, people began to take an interest in what science could offer in practical terms. This shift in perspective was greatly encouraged by the enterprising and developing bourgeoisie.

In astronomy, observational methods were refined, instruments improved, and planetary motion tables made more accurate. The mayor of Danzig, amateur astronomer Jan Hevelius, published the beautifully illustrated *Selenography* — a description of the Moon. People marvelled at the lunar Apennines and Alps, the Sea of Clarity and the Sea of Tranquillity. From an ideal Aristotelian body, the Moon was finally recognised as a planet similar to Earth.

The astronomer Giovanni Domenico Cassini, working in Paris, discovered the rotation of Mars and Jupiter. And if planets are Earth-like, why deny rotation to Earth itself? Is this not, once again, confirmation of the God-defying but wise Copernican theory?

French astronomers carried out important work determining the distances to the Moon, the Sun, and the nearest planets. The diameter of the solar system, limited by the orbit of Saturn — the "highest planet" — reached nearly three billion kilometres. An almost inconceivable figure... Meanwhile, the Dane Olaf Römer, observing eclipses of Jupiter's satellites, calculated the speed of light, arriving at almost three hundred thousand kilometres per second.

In general, of course, there were discoveries, but they were clearly of a practical nature. There was also another

task, whose attempted solution played a major role in the development of astronomy.

In the seventeenth century, there was still no method for precisely determining such an important coordinate on the Earth's surface as longitude. Meanwhile, the colonial ambitions of the advanced nations demanded reliable maritime transport. For the first time in history, to solve a scientific problem, states themselves were compelled to establish scientific institutions — and not only establish them, but also fund and encourage them. In 1667, to refine terrestrial coordinates using observations of celestial bodies, the Royal Observatory was established in Paris; eight years later, one was founded in Greenwich, and subsequently in Saint Petersburg in 1725.

The first director of the Greenwich Observatory was John Flamsteed, a diligent and conscientious observer who, according to contemporaries, possessed an incredibly tedious character. King Charles II, in his generosity, conferred on the new director the splendid title of "Royal Astronomer," compensating for the meanness of the royal stipend with the pomp of the title. The English are great lovers of tradition. Wishing to preserve this grand old title for the director of the Greenwich Observatory to the present day, they eventually increased its monetary equivalent. The position became not only honourable but also lucrative. A tradition was born.

The task of the first Royal Astronomer was:

> "to apply the greatest care and diligence to the correction of tables of the motions of the heavens and the positions of fixed stars, and equally to determine the much-desired longitudes of places, for the improvement of the art of navigation."

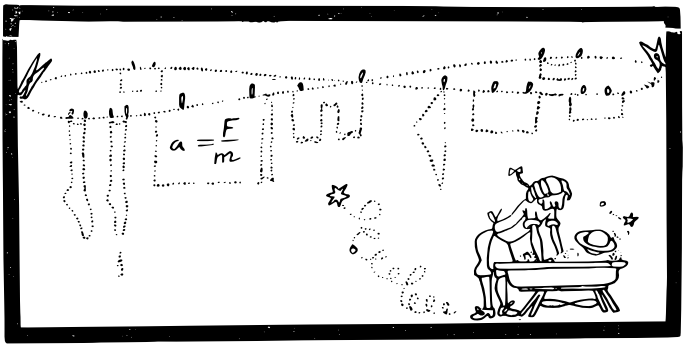
The decree, however, did little to help. Several years later, having despaired of obtaining a solution to the "much-desired" problem, the English Parliament, at Newton's suggestion, announced a competition for the development of the most accurate method of determining longitude at sea. A prize of £ 20,000 — a very substantial sum for the time — was offered for an error of no more than 0.25 degrees (approximately 30 miles). Later, two additional prizes were established for less precise solutions: £ 15,000 for an error of 40 miles, and £ 10,000 for an error of 60 miles. The problem was finally solved only in the nineteenth century, first by the Russian navigator M.A. Akimov, and then by the Frenchman Saint-Hilaire, who proposed a modern method for jointly determining latitude and longitude suitable for shipboard conditions.[14]

This example somewhat changes the conventional view of Newton's modest activity in Parliament. It is usually assumed that, absorbed in his own thoughts, Isaac Newton sat through sessions of the House of Commons without participating and spoke only once. Having received the formal permission of the chairman, the scholar modestly asked a clerk to close a window that was letting in a draft. After that, he again immersed himself in his thoughts.

Of course, this is an anecdote, and the author tends to

[14] While Newton advised Parliament on longitude accuracy in 1714, he didn't propose the famed prize. The claim that the longitude problem was solved in the nineteenth century by M.A. Akimov and/or Saint-Hilaire is incorrect or highly doubtful. The longitude problem was effectively solved in the 1760s by John Harrison through the development of the marine chronometer H4. The names Akimov and Saint-Hilaire are not recognised as primary solvers of the longitude problem in standard historical accounts. – DM

think it was invented by the English, eager to create an aura of extraordinariness around Newton's name.



The solution to many problems of that era rested on the question of the force governing the motions of the planets, motions in general, and free fall in particular. People desperately needed at least one quantitative law of nature, one that would allow them to move from mere discussion to concrete action.

Kepler processed Tycho Brahe's observational data and, using his laws, formulated the conditions of the problem that needed to be solved.

Then Galileo established the principles and rules according to which the problem of the long-sought force was to be addressed. Huygens, having developed the theory of the pendulum, showed the path to its simplest solution. And it was Newton who ultimately solved it, giving the world the law of universal gravitation.

Interestingly, Newton and Huygens, despite being well aware of each other's work, remained unacquainted for a long time. Their first meeting occurred rather curiously. Huygens arrived in London and was invited to present a paper at a meeting of the Royal Society. Newton received a similar invitation. Both, as if by design, chose the least successful topics for their presentations. Thus, Huygens presented his incorrect theory of gravitation in Newton's presence, while Newton, in turn, demonstrated erroneous results on the measurement of double refraction in Spanish spar. (It should be remembered that Huygens was the author of the brilliant theory of double refraction.) Naturally, after exchanging such presentations, the two parted ways without ever feeling mutual sympathy.

3.8 Newton's Apple

> An apple, falling, interrupted
> The depth of Newton's meditation,
> And they say — I won't vouch
> For sages' guesses or education —
> He found by this a way to show
> In clear fashion the force of attraction.
> With the fall, and thus with the apple, only he
> Could grapple, since Adam's earliest days.

Byron wrote this. The anecdote about the apple is well known. But how does a fruit dropping from a branch relate to the dry formula of a law?

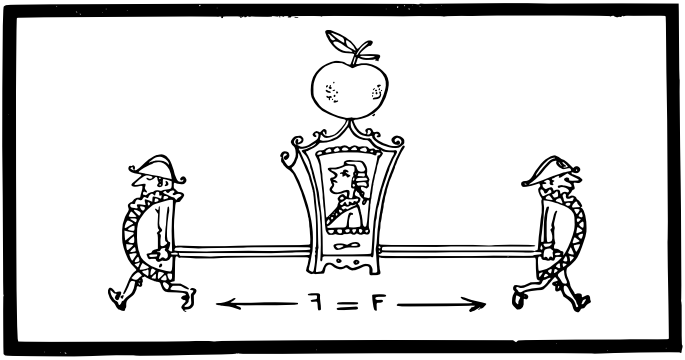
The story of the apple has some degree of authenticity. Newton's contemporary Stekelay wrote late in life:

> "After lunch the weather was hot; we went into the garden and drank tea in the shade of several apple trees; it was just the two of us. By the way, Sir Isaac told me that he was in exactly the same situation when the idea of gravitation first came to him. It was prompted by a falling apple, while he sat absorbed in thought. Why does the apple always fall straight down, he wondered, why not sideways, but always toward the centre of the Earth? There must be an attractive force in matter, concentrated at the Earth's centre. If matter attracts other matter, there must be proportionality to its quantity. Therefore, the apple attracts the Earth just as the Earth attracts the apple. Hence there must exist a force, like that which we call gravity, extending throughout the universe..."

"This story was known to few," wrote Academician Vavilov, "but the whole world became familiar with the anecdote-like retelling by Voltaire, who heard of the incident from Newton's niece." Voltaire's tale was a success. Soon, enterprising heirs began showing the apple tree that had served as the "main occasion" for the creation of Newton's *Principia* — the great work that became, for many years, the bible of the new science.

Equally important for Newton's developing theory were ideas expressed in 1666 by the Italian Borelli. Borelli studied the motion of Jupiter's satellites and concluded that although celestial bodies certainly attract one another, their rotational motion produces a tendency directed away from

the centre of rotation. If these two tendencies balance, the satellites remain at a constant distance from the planet. In exactly the same way, the planets move around the Sun...



Borelli reasoned that if a planet is at such a distance from the Sun and moves at such a speed that the tendency away from the centre (what we would now call, economically, "centrifugal force") is less than the force of attraction, the planet would begin to spiral towards the star until the two forces balanced. Yet, due to inertia, discovered by Galileo, the planet would overshoot the neutral orbit and approach the Sun closer than its equilibrium position. Its remaining velocity would then allow the centrifugal force to overcome attraction, and the planet would spiral away from the star once more.

Borelli's hypothesis contained not a line of mathematical proof. He simply postulated the existence of an attractive force and logically deduced the curvilinear motion of

the planet. Newton, however, was not satisfied with such Cartesian reasoning. A consummate mathematician, he preferred quantitative investigation. Breaking free from the constraints of Cartesian philosophy, Newton adopted the maxim, "I frame no hypotheses," and began to calculate.

One of Newton's few friends, the astronomer Edmund Halley, recalled that many at the time were concerned with the problem of gravity in relation to planetary motion. In 1683, Halley was able, using Kepler's third law, to derive the inverse-square decrease of gravity with distance. Yet he could not obtain the elliptical orbit of a celestial body. On one occasion, Halley met in a London coffeehouse with the architect Wren, builder of the famed St. Paul's Cathedral, and the well-known Robert Hooke — a physicist, mathematician, experimenter, and theorist, endlessly full of ideas but completing few of them.

The conversation turned to science and its problems. It became clear that all three had devoted considerable time and effort to the same question, yet none could claim success. Wren, the wealthiest of the trio, in true English fashion, proposed a wager: to award a prize to whoever could prove that under a force of gravity decreasing inversely with the square of the distance, celestial bodies must move in elliptical orbits. Nevertheless, neither the spirit of competition nor Wren's tempting offer brought about success.

Once, visiting Newton, Halley told him about the dispute and the wager made in the coffeehouse. Some time

later, when chance again brought the young astronomer to Cambridge, Newton informed him that he already had the solution in hand. Exactly a month later, Halley received from Newton the manuscript of a brief memoir On Motion. At Newton's request, the memoir was not published in the Royal Society's journal, but it was registered in case of disputes over priority.

The situation in England at that time was tense. After the death of King Charles II, party struggles intensified. Newton, who had patrons in both factions, had to be extremely cautious. He generally disliked disputes. Yet fate laid before him a path on which no independent step could be taken without debate.

While working on gravity, Newton devoted much attention to the motion of the Moon. This was a very complex mathematical problem, because the lunar motion was influenced not only by the Earth's attraction but also by the Sun's. In mathematics, this is known as the famous "three-body problem": three large masses, with known initial velocities and positions in space, and the task is to determine their subsequent motion.

Despite its apparent simplicity, obtaining a complete solution to this problem proved extraordinarily difficult.

To verify the results of his calculations, Newton needed observational data on the Moon. He repeatedly appealed to Flamsteed, who observed the night sky. However, the stubborn and irritable royal astronomer had no intention of indulging "the whims of Mr. Newton," as he often expressed

it. This led to complications and unpleasant quarrels.

Newton thought relentlessly. Discarding everything else, he focused all his formidable mental energy on the question of the Moon's motion. At one point, he even complained to Halley that working on lunar theory gave him headaches and woke him so frequently that he wished he could never think about it. Eventually, Halley, to help his friend, published Flamsteed's observational results without his knowledge, earning, quite justly, the nickname "malicious thief" from the royal astronomer. Thanks to this, Newton was able to complete his work on the *Principia*.

It was Flamsteed's tables that convinced Newton that the acceleration of the Moon's motion and the acceleration of falling bodies on Earth corresponded very well with the law of gravitational force varying inversely with the square of the distance. This led to a decisive conclusion: the force that causes objects to fall on Earth and the force that keeps the Moon swiftly orbiting our planet are one and the same.

Thus, the three fundamental laws of mechanics, along with the law of universal gravitation, became universal for both Earth and sky. A year after the appearance of the brief memoir *On Motion*, largely thanks to Halley's persuasion and insistence, Newton produced the full manuscript, later published as the first book of the *Mathematical Principles of Natural Philosophy*.

"Sir Isaac developed the ore that I dug up," Flamsteed remarked, venomously though not without bitterness.

"If he dug up the ore, then I fashioned it into a golden ring," retorted Newton, who, despite his dislike of disputes, disliked even more when his work was discussed without due respect and the last word was left to an opponent.

Newton's *Principia* was an astonishing book. "In the persuasiveness of its argumentation, supported by physical evidence, this book has no equal in the entire history of science," writes J. Bernal.

> "Mathematically, it can be compared only with Euclid's *Elements*, and in the depth of physical analysis and influence on the ideas of the time — only with Darwin's *Origin of Species*."

One of the most important general philosophical conclusions from its content was that *the laws of nature are universal, applying equally to both terrestrial and celestial objects*. Newton's principles explained the motions of bodies in space and on Earth without additional conditions, hypotheses, or assumptions. By contrast, Descartes required the hypothesis of vortices, and hence of an ether, to explain the same phenomena. Newtonian physics was stricter and more coherent than Cartesian physics.

3.9 The Universe of Sir Isaac — And Was Newton a Newtonian?

With the publication of the *Principia*, Newton's fame became universally recognised, and his authority unquestion-

able. His work effectively summarised a thousand years of knowledge about the simplest forms of motion of matter. Contradictory and confused hypotheses were replaced with rigorous and clear mathematical demonstration, providing a framework for solving any problem, whether in astronomy or applied mechanics. His law of universal gravitation justified the Copernican model of the solar system and made it possible to calculate the full orbit of any body orbiting the Sun, even when an observer could see only part of the points marking the celestial body's position. Using Newton's laws, Halley calculated the elongated orbit of a comet and its period around the Sun. And as if to confirm the scientist's fame, the celestial body appeared again at the predicted time sixteen years after Halley's death.

For his work, Newton retained Descartes' classical title, *Principles of Philosophy*, modestly narrowing it to *Mathematical Principles*.... However, in the work itself he subjected the then-dominant, vague Cartesian "philosophy of hypotheses" to severe critique. Newton repeatedly spoke of his desire to construct physics in the image of geometry — that is, to derive, mathematically, all necessary theorems and lemmas from precisely formulated axiomatic principles that required no further proof. That elements of hypotheses were embedded in the principles themselves, Sir Isaac prudently kept silent about.

This powerful method of constructing a theory is far more unassailable than the method based on hypotheses. Hypotheses are born and die, replaced by new ones. Principles, however, can only be supplemented and perfected.

These ideas, adopted by the Newtonians, almost elevated the creator of the law of universal gravitation to an Aristotelian rank, generating a drive toward axiomatic thinking. We shall encounter this tendency again in cosmology.

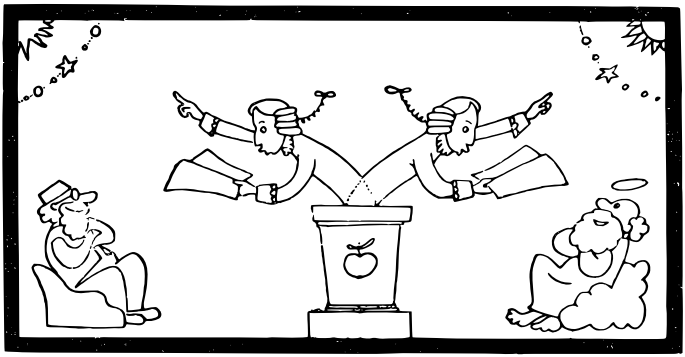
From the very moment of the *Principia*'s publication, fierce disputes arose between proponents of the new method and the Cartesians. Voltaire, who did much to popularise Newton's ideas on the continent, wrote of this battle of ideas:

> "If a Frenchman comes to London, he will find a great difference in philosophy, as well as in many other matters. In Paris, he left a world full of matter; here he finds it empty. In Paris, the Universe is filled with ethereal vortices, whereas here, in the same space, invisible forces operate. With the Cartesians, everything is achieved by pressure, which, truth be told, is not entirely clear; with the Newtonians, everything is achieved by attraction, which, however, is no more clear."

Newton applied his law to the myriad stars performing their daily circuit across the night sky, and from this arose the requirement of a uniform distribution of stars in space. Any local concentration, according to the law of attraction, would be unstable. The forces of attraction would inevitably gather the stars of such a cluster into a single heap... The condition of uniform distribution, therefore, demanded an infinite number of stars.

Let us imagine for a moment that the number of stars

is limited. Then the outermost, most distant stars would experience the force of attraction only from the celestial bodies located within the cluster. And this means that not merely local groupings, but all the stars of the universe would have to come together... The assumption of an infinite number of stars thus required an infinite space to contain them.



How, then, did Newton conceive the structure of the world? He addresses this in his *Principia*, concluding the "Definitions" section with a "Scholium," which has since become one of the most famous passages in the book. He begins with notions of space and time:

I. Absolute, true, and mathematical time, of itself and by its own nature, flows uniformly without relation to anything external, and is called duration. Relative, apparent, or common time is some measure of duration by the means of motion, perceived by the senses,

and used in daily life instead of true mathematical time, such as hours, days, months, and years.

II. Absolute space, by its own nature, without relation to anything external, remains always similar and immovable.

A complex concept, which in the future would spark many disputes. On the one hand, it is materialism — Newton fully recognises the objective existence of space and time.[15] On the other hand, the absolute character of both categories, unconnected to real phenomena or matter, gives a nod to metaphysics.

[15] Newton's Scholium in *Principia* defines absolute space and time as real, independent entities — uniformly flowing time and immovable space — but calling this "materialism" is anachronistic and misleading. He integrated them into a theological framework (space as God's "sensorium"), not modern materialist ontology. His framework is better understood as a form of realism about space and time, embedded within a theologically informed worldview. – DM

The third book of the *Principia* is devoted to the exposition of the system of the world. It draws the final line under the new worldview established by Copernicus. Newton wraps his proofs and assertions in a strict mathematical form, accessible only to a few true scientists, in order to avoid the gossip of those "who, having insufficiently understood the initial propositions... and not having discarded prejudices long held, would embroil the matter in disputes."

However, in the nine hypotheses prefacing the exposition, Newton makes the points perfectly clear.

Hypothesis IV. The centre of the system of the world is at rest, this is acknowledged by all, while some suppose that the Sun occupies the centre, others that it is the Earth.

Hypothesis VI. The five principal planets — Mercury, Venus, Mars, Jupiter, Saturn — encompass the Sun with their orbits."

Thus was born Newton's universe — infinite in space, uniformly filled with matter, and... infinite in time. Though in time, only directed toward the future, not the past. In the past, there existed a Creator God. If one extends the cosmological principle into the past, the Lord would be unemployed. This did not satisfy Newton. And so he received considerable criticism from Leibniz and from the entire German faction devoted to his idol, for portraying God, like Descartes' God, merely as a creator who does not intervene in the workings of the world-machine.

Newton was a deeply religious man. He took greater pride in his title of theological scholar than in that of brilliant mathematician and philosopher, considering his main works to be the numerous theological treatises he produced. These treatises, today, if they hold any value, are of historical interest only. Such a conviction of the truth of one's calling is, however, a rather common phenomenon in history.

The triumph of Newton's rigorous method over Cartesian free-thinking was greatly aided by the fact that the wave of intellectual freedom born of the Renaissance had largely subsided by Newton's time. Developing capitalism demanded compromises: between the bourgeoisie and the nobility, republics and monarchies, science and religion... Orthodox theologians conceded, allowing Newton's universe. But science also had to yield, permitting religion to employ scientific results to affirm the essence of God. Eager followers of the great Englishman were quick to exploit his assertions and authority from the *Principia*.

Space and time are infinite? Very well, they are not tied to matter; they are "supermaterial" — read "divine." Descartes' ether and vortices — false? Even better! Then the forces moving matter are transmitted through emptiness without any material carrier. This could only be interpreted as divine providence... And so forth.

It would hardly be fair to blame Newton for the reactionary conclusions drawn by the Newtonians. His natural philosophy supported not only conservative nonsense, but also Voltaire's free-thinking and the atheism of French materialists. Faraday knew by heart Newton's famous letter to Bishop Bentley and frequently cited it. In that letter, the scientist explicitly told the theologian that he did not intend to attribute the action of gravity at a distance to divine intervention:

> "... Gravity must be caused by some agent acting according to certain laws. What kind of agent — material or immaterial — I leave to the reader's consideration."

He expresses the same in the *General Instruction* concluding the third book of the *Principia*:

> "...so far I have explained the celestial phenomena and the tides of our seas on the basis of the force of gravity, but I have not indicated the cause of gravity itself... The cause... I have so far been unable to deduce from phenomena, for I invent no hypotheses."

Lomonosov stated directly: "Newton did not acknowledge attractive forces in his lifetime and became their administrator only after death through the efforts of his disciples."

And the "disciples" eagerly adapted the *Principia* to glorify God. And not only the disciples.

> O thou, infinite in space,
> Living in the motion of matter,
> Eternal in the flow of time,
> Without faces, in three faces of divinity—

wrote Derzhavin in his ode *God*. To ensure readers grasped the philosophical sense, the poet added a note:

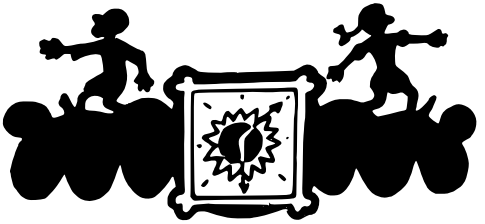
> "The author, besides the theological concept of our Orthodox faith, here understood three metaphysical faces, that is, infinite space, the uninterrupted life in the motion of matter, and the endless flow of time, which God unites in Himself."

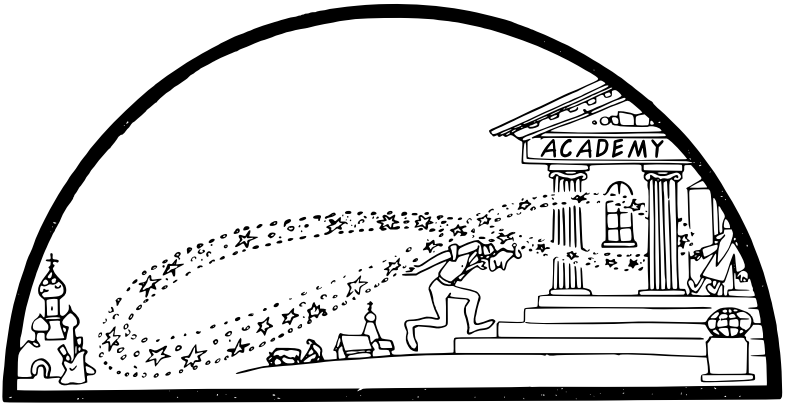
One cannot fail to recognise the brilliance of this exposition of the "perfect cosmological principle" of the eighteenth century.

Thus, Newtonian principles nourished the widest range of viewpoints. For our purpose, one fact is decisive: through Newton, the idea of an eternal and infinite universe, governed by the laws of flat Euclidean space with its three dimensions, was firmly established. Such became the picture of the world at the end of the first period of modern natural science, which, as Engels put it, "concludes in the realm of the inorganic world with Newton."

Part II.

Successes and Doubts





4. The Star-Struck Philosophers

In which the author, continuing to knock on open doors, demonstrates the infinity of the universe. Yet the perceptive reader, for whom this has long been clear, meets along the well-trodden path of proofs some interesting people and therefore does not come away empty-handed.

In the eighteenth century, interest in science broke out of the borders of the countries that sought to monopolise this form of public consciousness and rolled, rolled across the entire globe. Soon no royal, imperial, tsarist, or, at the very least, elector's court could think of prestige without having its own Academy of Sciences. Especially since establishing one was not prohibitively expensive.

Academics were paid sparsely and irregularly. Greater sums went to those who, with tricks or solemn odes, could attract the attention of monarchs. The proverb "he who pays, orders the music" was already true two hundred years ago. And yet, it was a colossal step forward; no, not a step, a triple leap... Science flourished most vigorously in the newly created academies.

In 1701, by decree of Tsar Peter I, the Navigation School was established in Moscow — the first Russian institution training future navigators and surveyors. Here, too, the first astronomical observatory was built, where noble youths for the first time learned of Copernicus's heliocentric system and Newton's laws.

Once, evaluating Newton's role in world science, the English poet Alexander Pope wrote a famous couplet, which has been translated countless times and always differently. In the original it reads:

> Nature and nature's laws lay hid in night.
> God said "Let Newton be!" And all was light.

These lines will resurface in the history of cosmology to mark the achievements of twentieth-century science. But

for now, the author wishes to remind readers of the first paraphrase of the couplet, made by Mikhail Vasilyevich Lomonosov, which precisely characterises the period under discussion:

Russia was shrouded in gloom for many years. God said: "Let Peter be!" And there was light in Russia!

New currents, as usual, were first met with malicious hissing, and then with open resistance from reactionary circles clinging to the old way of life. Even in 1719, a book was published in Saint Petersburg still expounding the Ptolemaic system. The work was titled: *A Brief Description of the Terrestrial Sphere, Compiled by Jagan Hibner*. In this "brief description" there are rather remarkable lines:

> "... since it is written in the Holy Bible that the Sun moves around, and the Earth is immobile, one ought to believe the sacred scripture more than human opinion. This argument was particularly preserved by the Danish mathematician Tycho Brahe, to which all still agree, who are reluctant to contradict the Holy Scripture."

Resistance to the heliocentric teaching came not only from people of the church. Many educated people were firmly convinced that the truth about nature ought not to be revealed to the "base common people," claiming that it would only create confusion in the minds and souls of the immature.

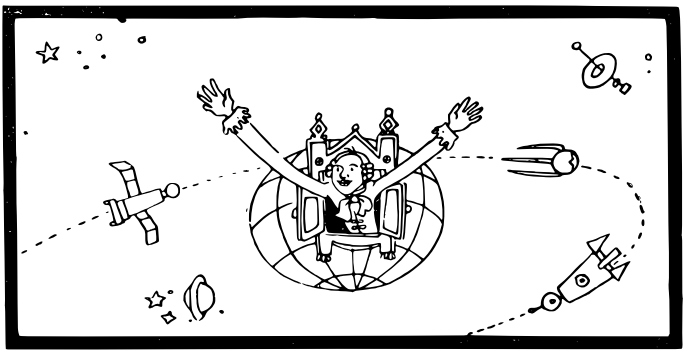
4.1 The World in Lomonosov's Hands

In 1724, Peter I established the Saint Petersburg Academy of Sciences. The development of science was explicitly one of the points in his plan for transforming Russia. Admittedly, the newly created institution initially had to be staffed with invited foreigners. However, if one considers that among the first professors of the academy, alongside a certain number of charlatans and showmen, there were such outstanding figures as L. Euler, D. Bernoulli, G. Bilfinger, and J. Delille, the "Tsar-woodworker's" reliance on foreign teachers can be excused.

In 1741, Mikhail Lomonosov returned from Germany to Saint Petersburg as a student of the academy. Behind him were years of study and debates that had shaped the worldview of Russia's first academician.

It was not easy for Lomonosov to break through the dense crowd of foreigners filling the academy. The situation was further complicated by the fact that by this time the Saint Petersburg Academy no longer had prominent physicists. The famous Germans, having completed their contracts, returned to their beloved fatherland without leaving a school behind. Lomonosov found himself almost alone before an enormous array of diverse physical and chemical problems. Moreover, he was the first Russian academician in the fields of astronomy, geology, geography, history, economics, and philology, all of which were piled with problems that demanded solutions.

The demands of his time, combined with the exceptional talent of Mikhail Vasilyevich Lomonosov, made him an encyclopaedic scientist, even though such a type of scholar was already quite rare in the eighteenth century. The accumulation of the nation's wealth, his personal renown, and the relief of labour and life for his people were the incentives that drove Lomonosov to tackle the most diverse problems. These incentives were spurred by the rapid economic and cultural development of Russia and the advancement of science itself.



From around 1748, correspondence developed between Lomonosov and L. Euler, the celebrated mathematician and president of the Berlin Academy. Euler gave high praise to Lomonosov's works:

> "All these writings are not only good, but excellent, for he explains physical and chemical matters, the most necessary and difficult, which were entirely unknown and impossible to interpret even for the most

> ingenious minds, with such thoroughness that I am completely confident in the accuracy of his proofs. In this case, I must also acknowledge Lomonosov's gift of the happiest ingenuity for explaining physical phenomena."

A year later, seemingly confirming Euler's opinion, Lomonosov formulated, in a letter to him, essentially the universal law of conservation of matter:

> "All changes occurring in nature happen in such a way that if something is added to one thing, it is taken from something else..."

The world of science owes much to this remarkable encyclopaedic scholar.

Lomonosov's views on the development of nature over time were notable. According to the Bible, the Earth and everything upon it were created by God in the form they presently exist. Observing the variable stars in the heavens, Lomonosov reasoned that if changes occur in the depths of the universe, can such an insignificant planet as Earth be considered unchanging?

He resolved his position regarding the great debate between the Copernican and Ptolemaic systems decisively and irreversibly, expressing it in his pointed verse:

> "Two astronomers once met at a feast
> And debated fiercely in the heat.
> One insisted the Earth revolves around the Sun;
> The other said the Sun carries all the planets along.
> One was Copernicus, the other Ptolemy.
> Then the cook settled it with a smile.

> The host asked: do you know the stars' motion?
> Tell me, how do you reason on this doubt?
> He answered: Copernicus is right;
> I'll prove the truth, though never on the Sun.
> Who has seen such a simple cook,
> Turning the hearth around the roast?"

It was precisely the work of Lomonosov and other leading academicians that ensured that, by the beginning of the second half of the eighteenth century, the Copernican system became the foundation of instruction not only in all military and civil schools in Russia, but also in ecclesiastical institutions. Perhaps nowhere else did such an interest in astronomy awaken so strongly.

A whole generation of distinguished domestic astronomers marked this period. It is difficult to say whether the labours of these early Russian astronomers, or their restless, inquisitive spirit—passed down to us, the readers—did not inspire, in 1957, the launch of the first Soviet satellite; in 1961, the first Soviet cosmonaut; in 1970, the first lunar rover and the remarkable series of automated missions to Venus; and in 1971, the first orbital station Salyut.

It is regrettable that the achievements of space exploration and the construction of the largest telescopes in the world are not the subject of this book. Our task is the universe—immense, eternal, and infinite. The sole beacon in its darkness remains, for now, the law of universal gravitation formulated by Isaac Newton.

4.2 The Universe as a System — Early Speculations

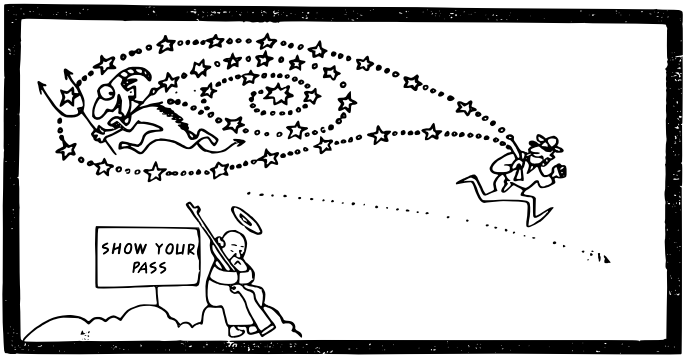
Newton's universe required a uniform distribution of innumerable stars across infinite space. Yet a glance at the night sky revealed something quite different. Constellations, star clusters, and "empty" black gaps painted a chaotic picture, far from uniform. Could Newton have erred somewhere in his reasoning?

This thought occurred to many, despite the weight of Newtonian authority. In the mid-eighteenth century, in Stockholm, Sweden, there lived a certain Emanuel Swedenborg. He lived "without any particular profession, on his own, fairly considerable means." Initially, Swedenborg was captivated by natural philosophy. He studied minerals and engaged in crystallography, and his works contributed to the development of these sciences.

But trouble came when Swedenborg turned to subtler and more mysterious matters than natural creations. He became interested in the human soul and its destination after leaving the physical body. He explored whether it was possible to communicate with souls freed from earthly shells. In short, Swedenborg delved into mysticism. He discovered remarkable abilities as a medium and began dispensing advice freely.

For example, creditors brought a considerable claim against the widow of a Dutch envoy at the Swedish court,

alleging that her deceased husband had been careless and left substantial debts. Swedenborg immediately intervened. Communicating with the spirit world, he conversed with the deceased and learned the location of a secret repository containing the creditors' receipts. The resulting scandal was enormous, and the fraudsters were publicly chastised across Europe. Nevertheless, people did not stop borrowing money after this incident.



Next, while in Gothenburg, located about fifteen miles from Stockholm, Swedenborg "saw" with his inner vision a fire in the capital and warned those around him.

Rumours about the Swedish medium's abilities were utterly incredible. This was aided in no small part by the fact that Swedenborg, out of modesty and benevolence, never kept any secrets. Receiving information about the otherworld from firsthand sources, he gladly composed voluminous tomes of his visions and commentary. His

mystical philosophy became very popular both among his fellow countrymen and abroad.

Not content with the substantial memoir *Essay on Philosophy and Mineralogy*, he created the eight-volume work *Secrets of Heaven*. "Eight volumes, filled with madness," — so Kant described this work. Yet among the many delirious ideas, Emanuel Swedenborg expressed a very curious thought. Observing the starry sky along the thick seam of the Milky Way, he stated that the entire visible world of stars is a *single dynamic system*. Moreover, he proposed that such systems in the universe are not one or two, but innumerable, since the infinity of the world cannot be doubted...

Curious, isn't it? The general concept of Sir Isaac acquires some concrete features. Unfortunately, these ideas were first inspired by mystical aspirations and, unsupported by any concrete evidence, were a typical example of speculation. Nevertheless, it is always useful to note a kernel of common sense even in mystical ramblings. Who knows, it might take root and develop? Especially since Swedenborg began his flirtations with the supernatural only after he expressed the idea described above.

Around the same time, five years after Swedenborg, Thomas Wright became interested in the structure of the stellar world. He was the son of a carpenter from the small village of Byers Green near Durham. A self-taught man, Tom Wright rose to become an astronomer. In this field he produced several original investigations and hypotheses.

Thus, studying the rings of Saturn, he stated quite firmly that they consist of solid particles. It should be recalled that at the time there were widely differing opinions on the matter. Some believed the rings to be liquid, others gaseous...

Observing the night sky, Wright advanced a hypothesis that in England came to be known as the "millstone theory." In his view, the Milky Way, together with the stars surrounding it, forms a vast disc whose diameter is far greater than its thickness. Since the Sun, along with its entire family, is situated not far from the centre of this disc, people see the cluster of stars, as it were, edge-on. That is why the Milky Way encircles the whole earthly sky. It is simply the direction along the great diameter of this "millstone" — a direction in which an enormous number of stars merge, at unimaginable distances, into a pale milky glow.

In 1755, the presses of Königsberg printed a modest anonymous work with the lengthy and detailed German title *Universal Natural History and Theory of the Heavens*. Yet this work at first never truly saw the light. The publisher went bankrupt, and his warehouse was sealed by the authorities. Later, the author himself lost interest in natural philosophy, and his subsequent writings overshadowed this modest brochure. It lay forgotten on archive shelves, outliving its time in obscurity. A hundred years passed. Its unsuccessful author — a privat-docent of Königsberg University — grew in human memory into the figure of the greatest philosopher, the creator of a new doctrine of

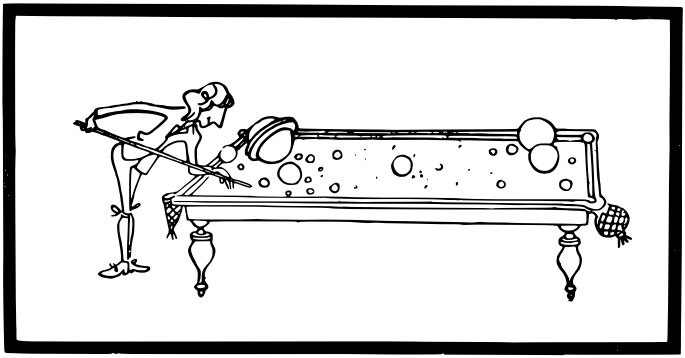
knowledge, Immanuel Kant. Only in the mid-nineteenth century did humanity recall his early work. It remembered, admired, and, as so often happens, belatedly began to sing its praises...

4.3 Immanuel Kant — Natural Philosopher

Speaking of Kant, one must briefly recall the circumstances in which this modest yet great man lived and thought.

Born into the family of a fairly prosperous saddler, the boy lost his mother at an early age. At nine he was sent to the Collegium Fridericianum. Immanuel was the best pupil in his class. Yet he enjoyed neither authority nor popularity among the other boys. He was frail, shy, absent-minded, and forgetful. His eight years at school instilled in Kant a hatred of his childhood and of the school itself — a "religious barracks of gloomy fanaticism" — but also gave him a solid grounding in Latin language and literature.

Then followed the university. His father did not assist him with a single coin. In these years, however, Kant's life differed little from that of other students. Together with his companions he rented a room. They shared a single coat among three. He took a liking to billiards and became so skilful at the game that at times he earned his living by it. His interests were concentrated chiefly on mathematics and natural science, which at that time formed part of philosophy.



After leaving the university, Kant resolved to devote himself to science. Poverty, however, prevented him from immediately entering an academic career. For nine years he worked as a private tutor in various households in Königsberg. Only in 1755, at the age of thirty-one, did he obtain a position at the University of Königsberg as a privatdocent.

The beginning of Kant's lectures attracted a considerable number of listeners, and he hoped for rapid advancement. But alas... "He who dedicates himself to the University of Königsberg thereby takes a vow of poverty," remarked Kant's colleague, Professor Kraus. His words reflected reality.

To maintain a tolerable standard of living, Kant was forced to take on an extraordinary teaching load. He lectured simultaneously on logic, mathematics, metaphysics, mechanics, theoretical physics, physical geography, gen-

eral natural history, arithmetic, geometry, and trigonometry — thirty-four to thirty-six hours a week. Even by modern standards, such a burden is excessive. At the same time, through an additional post as librarian of the royal library, he managed to remain informed about all philosophical trends and developments.

The eighteenth century was the age of scepticism. If Descartes, Bacon, and Spinoza, while preaching doubt, still believed in the boundless powers of reason and sought the proper method for applying its capacities, Newton's contemporary John Locke maintained that the limits of knowledge are inherent in the human being. Gradually, developing doubt led to the denial of the very possibility of knowledge. By Kant's time, sceptical philosophy concluded that cognition cannot penetrate into the realm of causes underlying observable phenomena.

In Königsberg there lived then Johann Georg Hamann, a gifted autodidact with fragmentary education. Making the contradictions and confusions of his own life the starting point of his philosophy, he taught that all knowledge and philosophy are nothing but error. He called for replacing knowledge with faith — natural faith, the faith of an innocent child's heart. Such a philosophy, requiring no effort from a person, has always found admirers. Johann Hamann achieved recognition and acquired the title of the "Magus of the North."

At the same time in France, Jean-Jacques Rousseau was writing. The profound immorality and cynicism of the

educated strata of French society, set against oppression and widespread popular misery, led this philosopher to doubt the merits of culture itself. Although his scientific education was insufficient, his philosophical thinking often superficial, and his logic inconsistent, he called with such captivating eloquence for humanity to turn away from reason and return to nature — to a natural equality that would guarantee each person the inviolability of original rights — that he conquered minds and hearts.

From England, Kant heard the voice of David Hume, who maintained that the law of causality rests upon feeling rather than reflection. Consequently, all knowledge of nature, he argued, is based not upon knowledge in the strict sense, but upon belief in one's sensations.

These waves of scepticism could not fail to leave their mark on the young philosopher's views. In Kant's life, as in his work, biographers distinguish two periods. The first, the so-called pre-critical period, was devoted to natural philosophy. Here the starting point of Kant's thought was the admission of God as creator and the acceptance of the Newtonian causal mechanism for the subsequent development of the world. Thus, the ultimate striving of Newton and Leibniz to reconcile science with religion became the initial premise of Kant's natural philosophy in his pre-critical phase.

In 1754 he wrote two short essays anticipating the appearance of his *Universal Natural History and Theory of the Heavens*. The first was titled: "Has the Earth undergone

any changes in its rotation about its axis since the earliest times of its existence?" The answer he gave was affirmative. The second bore the shorter title: "Is the Earth ageing?" — and again the answer was yes.

Whatever Kant wrote in these works — whether about the gradual slowing of the Earth's rotation due to tides, the alteration of its shape under the destructive forces of water and volcanoes, or the regularity of ageing, decay, and death as the norm of nature — he stood firmly on materialist positions, advancing the idea of the development of the cosmos. Without even realising it, Kant spoke in the language of dialectics, referring to the transformation of quantitative accumulation into a new quality.[16]

[16] Although this commentary interprets Kant's early cosmological essays in materialist or even dialectical terms, such readings are retrospective. Immanuel Kant himself did not formulate a materialist philosophy, nor did he employ dialectics in the later sense associated with Georg Wilhelm Friedrich Hegel or Karl Marx. His approach is more accurately understood as a naturalistic attempt to explain cosmic and terrestrial processes within the intellectual framework of eighteenth-century philosophy. – DM

In concluding the essays mentioned above, Kant approached directly the question of "the original state of nature" and "the origin of the world bodies", promising in the near future to publish a "cosmogony, or an attempt to derive, on the basis of Newton's theory, the origin of the universe, the formation of the heavenly bodies, and the causes of their motion from the universal laws of the motion of matter". He fulfilled this promise, although he did not sign the unfortunate work.

The starting point of Kant's cosmogony was two features characteristic of our planetary system:

1. the motion of all known planets and their satellites in the same direction;
2. the relative emptiness of interplanetary space.

All the planets and their satellites known at that time rotated about their axes and revolved around the Sun in the same direction as the Sun itself rotates about its axis. Does this not indicate, Kant asked, a common cause that produced such uniformity?

The absence of visible matter in interplanetary space — and therefore the absence of material connections between celestial bodies — had led Newton to refrain from explaining the physical causes of planetary motion and to introduce God. Kant, however, followed a genetic approach. Admitting God as an initial "general cause", he then considered the universe in a process of development free from further divine intervention.

Such a compromise, known in philosophy as *deism*, was commonly in the eighteenth century among thinkers both in Western Europe and in Russia.

Kant supposed that, after the act of creation, there existed nothing but the "abyss of eternity", filled with countless atoms of matter. These atoms differed only in density and were distributed more or less uniformly throughout infinite space. In this boundless chaos only two forces operated: attraction and repulsion. From their interaction the first formations arose.

Naturally, the denser — and therefore heavier — formations attracted the lighter ones. As a result, solid material nuclei were formed, around which atoms of various densities gathered. Yet since every atom possessed not only attraction but also repulsion, the opposition of these forces

produced rotational motion.

As more and more masses of atoms fell and adhered to the nuclei, friction arose between the still unstable layers, heating the matter to an incandescent state. Thus the eternal darkness was pierced by the first ray of light: the first Sun ignited.

But atoms continued to fall upon it, increasing the volume of the luminary, the speed of its rotation, and the fire raging within. At the same time, as the volume grew, the force of attraction between the solid core and the atoms at the periphery weakened. Repulsion gained the upper hand. Then the outermost parts of the fiery sphere broke away from the core and, in accordance with a simple mathematical law, flew off tangentially into boundless space, until powerful forces curved their paths and carried them into orbit around the central star.

The detached fragments grew and heated in the same manner as the Sun, eventually reaching the size of planets. Thus, according to Kant, all the planets and all their satellites were born.

"The proposed theory of the formation of the planets," Kant wrote, "must be regarded as the most satisfactory, because it explains from one and the same standpoint both the origin of the masses and the origin of their motions, as well as the position of their orbits. The planets are formed from particles moving in definite circles; therefore the masses arising from these particles continue the same motions, with the same velocity and in the same direction."

In Kant's teaching, worlds are born, develop, age, and perish, dissolving into their constituent parts in order to yield to a new cycle. Thus Kant continues Newton's doctrine. In his conception, the entire cosmic process of development arises from the struggle of two opposites: the force of attraction and the force of repulsion. It is a striking example of unconscious materialist dialectics, expressed by the lips of the "greatest idealist" and agnostic he would later become.[17]

[17] While this doctrine extends the gravitational framework of Isaac Newton, the interpretation here that describe it in terms of materialism or dialectics are retrospective and do not reflect Kant's own philosophical position. – DM

It is difficult to overestimate the significance of Kant's memoir for the development of cosmological thought. Yet, regrettably, in its own time it played no role in that process. As a philosopher and author of the critical method, Kant became known throughout the world. But no one, including Kant himself, recalled his early cosmogonic work. For the philosopher it was a stage already passed; for his contemporaries... Yet contemporaries seldom recognise the genius living among them.

In 1794, when Kant was elected an honorary member of the St Petersburg Academy of Sciences, the presentation described him as a natural scientist, but among his works the *History of the Heavens* was not even mentioned. It was remembered almost a century later, when the French scholar Pierre Laplace developed a cosmogonic hypothesis similar to Kant's, which became known as the Kant–Laplace hypothesis.

4.4 Epilogue of the Philosopher's Life

At the beginning of the 1760s Kant became acquainted with the works of Jean-Jacques Rousseau. They made a profound impression upon him. Everything he had previously valued — reason, knowledge, culture, civilisation — seemed to collapse under the force of Rousseau's passionate eloquence. Kant began to feel that in these very achievements lay the cause of humanity's corruption.

"There was a time," Kant confessed, "when I believed that all this could do honour to mankind, and I despised the common people who know nothing. Rousseau corrected me... I learned to respect the human being." From that moment Rousseau decisively displaced Newton in his consciousness. Nature receded into the background, yielding its place to man. In that newly cleared space there eventually arose Kant's critical philosophy.

This revolution in philosophical thinking was preceded by a profound transformation of his inner and outer life. "Having lost faith in metaphysics, dominated by doubts about everything," writes I. Geller in his biography, "even about the existence of God, he for a time saw before him only the collapse of all youthful hopes, a life deprived of inner meaning, and an approaching, purposeless, lonely old age. So tormenting was this state that his thoughts more and more often dwelt upon death — sometimes with longing, sometimes with terror... But then came an inner revolution, long unconsciously maturing, yet appearing to

consciousness as a psychological 'explosion', a sharp turn toward a new life... Before him now stood only one task — the creation of a new, critically tested philosophy."

We shall not examine the questions of critical philosophy here; that lies beyond the scope of this book. Yet, to complete the account of Kant, a few words should be added about his life during the second period.

As a result of the Seven Years' War, the situation in Königsberg was tense. Russian troops advanced victoriously through Germany, and in 1760 they stormed Berlin.

Kant enclosed himself within the iron discipline of a regime he devised for himself. He hired an old soldier, Lampe, and once and for all gave him precise instructions. For more than thirty years thereafter, Lampe, with military conscientiousness, woke his master every day at exactly five o'clock in the morning and, regardless of any requests, made him rise.

Until the beginning of his lectures Kant worked; then he went to teach, and from nine or ten o'clock he worked again until dinner, which was served at one in the afternoon. He ate only once a day. The meal lasted long — two or three hours — during which he conversed with a small circle of friends. After dinner he smoked his single pipe of the day and went out for a walk lasting an hour. The remainder of the day he spent reading or reflecting. At precisely ten o'clock in the evening Kant went to bed.

The last decade of the philosopher's life coincided with

the Revolution in France and with a sharp strengthening of reaction in Prussia. In every "enlightener" the authorities saw a Jacobin, an enemy of Church and State. Kant did not escape this general fate.

In 1786 Frederick the Great died, and Frederick William II ascended the throne — a ruler of harsh and repressive character. At the coronation Kant, as rector of the university, greeted the new king and in the reply was honoured by being mentioned as a philosopher of world renown. Yet the new monarch soon issued a severe law on censorship, eliminating all freedom of the press and of speech. This was followed by the notorious religious edict. Henceforth every official, upon entering service, was required to swear an oath on the Gospel and to prove before the Prussian supreme consistory his religious reliability.

In this atmosphere of hypocrisy and suspicion, of denunciations and intrigue, Kant published his final work, *Religion within the Limits of Reason Alone*.

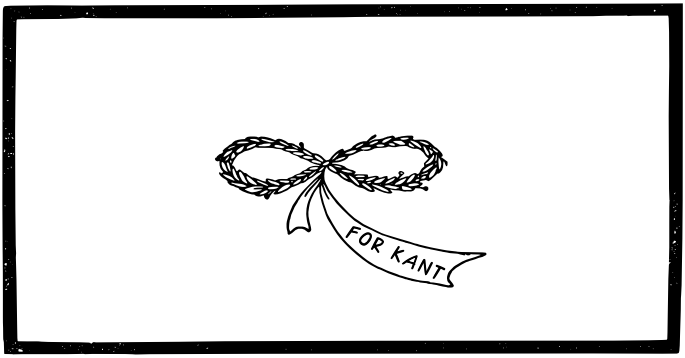
Less than a year later an order was issued to the philosopher in the name of "His Majesty":

> "Our highest person has long observed with great displeasure that you employ philosophy to distort and degrade certain principal and fundamental teachings of Holy Scripture and of Christianity, as you have done particularly in your book 'Religion within the Limits of Reason Alone', as well as in other shorter writings... We demand from you an immediate and conscientious account and expect that, in order to avoid our supreme displeasure, you will in future

refrain from such actions... Otherwise..."

What followed were unmistakable threats.

Kant was shaken by the decree. He was not a hero and did not hesitate to admit that "the force of necessity stands above philosophy." Moreover, there existed too great an inner affinity between Kant's moral doctrine and the social order of barrack-like Prussia. The duty of obedience to authority — an ingrained feeling in the upright and loyal subject — came into conflict with his chosen life's aim: the civic duty to serve truth. All this produced a severe moral crisis.



Kant replied to the decree with a written statement in which he declared it necessary, "as His Majesty's most faithful subject, solemnly to affirm that henceforth I shall entirely refrain from any public expression, whether in lectures or in writings, of my opinions concerning religion, whether natural or revealed."

Kant ceased to write. He abandoned teaching. The seven years that followed turned into a slow decline, until on 12 February 1804, having awakened in the morning and uttered his final word — "Good" — he closed his eyes forever.

The emperor could be satisfied. An emperor — what is an emperor? In essence, merely an office, and one not greatly accountable. Courtiers and salaried chroniclers will justify any mistake and elevate folly to the rank of revelation.

From the standpoint of universal human progress, Emperor Frederick was not worth the philosopher Kant's fingernail. And yet a flash of anger from a mediocrity brought down a titan. Was this truly so? No — it was not Frederick alone. It was society, upbringing, the accursed *Die Ordnung*[18], the sacred order revered by the disciplined German soul.

[18] Die Ordnung (German: "the order") refers to a culturally valued ideal of discipline, structure, and adherence to rules in German social life. – DM

On the philosopher's grave in the cathedral, within a splendid gallery erected in honour of the distinguished deceased, there was engraved in magnificent golden letters:

> The starry heavens above me,
> The moral law within me.

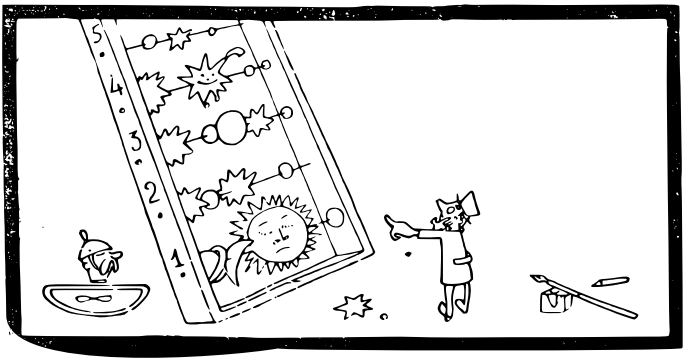
It is solemn and beautiful. Yet the gold of the inscription concealed a simple truth: *that any expenditure from the treasury upon a dead philosopher is preferable to revenues derived from a living one*.

4.5 Johann Lambert, Frederick II and the Universe

Newton's conception of the universe was simple and clear – provided one did not ask, "What is infinity?" or pose the equally awkward question, "What is eternity?" Philosophers were troubled by the vision of an infinite chaos of stars scattered through boundless space. The thought of disorder in the celestial realm deprived Christian astronomers of sleep. In such chaos one might easily lose even God. If only this confusion could be reduced to a system...

Johann Heinrich Lambert was the son of a tailor. According to the order of the "well-structured empire of the Prussian monarch", he ought to have inherited his father's needle. Such was the rule – Die Ordnung above all. It had entered into the flesh and blood of every German, especially every Prussian: order, and devotion to the adored monarch.

Yet Lambert did not become a tailor. From an early age he displayed remarkable mathematical abilities. He first entered employment at a factory as a bookkeeper. Later he became the personal secretary of a professor in Basel. Finally, he served as tutor and governor in the household of a Prussian courtier. It was almost the same path, the same steps, that had earlier been taken by Immanuel Kant, the saddler's son.



Johann Heinrich Johann Heinrich Lambert found time to think and to write. From his pen came several first-rate mathematical works. In 1760 he published his first astronomical treatise, devoted to determining the distances to the stars by their brightness. At the same time, Lambert began to shape his philosophical position. This was no simple matter. French by origin, he was drawn to the materialist freethinking of Voltaire. As a Prussian subject, he admired the emperor and was influenced by the German philosopher Christian Wolff. According to this apologist of the Prussian notion of harmony and purpose in nature, "cats were created to eat mice, mice to be eaten by cats, and the whole of nature to demonstrate the wisdom of the Creator," as Friedrich Engels wrote when criticising Wolff's flat teleology[19].

Reflecting on the structure of the universe, Lambert asked himself: "What must great purposiveness be like?" And he answered at once: "Above all, orderly!" From Wolff's

[19] Teleology refers to the explanation of phenomena in terms of purposes or ends, rather than solely by causes. It interprets natural or social processes as directed towards goals or final outcomes. – DM

standpoint, could one imagine a better order than that existing in the state of the adored monarch, where every estate knew its place? Peasants and craftsmen below, above them the burghers, and higher still the aristocracy...

In 1761 Lambert's book *Cosmological Letters on the Constitution of the Universe* was published in Augsburg. In it he set forth his cosmological views in full detail. He described a vast and infinite "hierarchical ladder" of cosmic systems. The Sun, with its planets and comets, formed the first and lowest step. The other stars, each surrounded by its own planets, were systems of the same first order. The cluster of stars visible in the earthly sky, with our luminary as an ordinary member, constituted a system of the second order. At the centre of this second-order system stood its own giant sun, and all the members of the system revolved solemnly around it.

Giant suns with their numerous retinues entered into systems of the third order, arranged in an analogous manner. To systems of the third order Lambert assigned the Milky Way. Here the size of the central luminary was already beyond imagination. Yet there must exist many such systems as the Milky Way. Lambert identified them with the tiny patches of nebulae[20] that observers had only recently begun to discover in various regions of the sky. The orders rose ever higher, increasing in geometric progression.

[20] From Latin *nebula* literally 'mist'. – DM

Lambert even attempted to determine quantitatively the sizes of systems of the second and third orders. There

is little point in citing those figures today, for they no longer carry scientific meaning. More interesting, however, is his explanation of why we do not see the giant suns of the higher orders. The philosopher dealt with the difficulty quite simply.

Since planets are destined to be the abodes of life, the suns of first-order systems must emit light — light being necessary for life. But the central luminaries of higher-order systems have no one to illuminate and no life to sustain. Therefore, they have no need of light. Lambert accordingly declared them dark. One can sense here the iron grip of purposiveness: "mice are created to be eaten by cats." It is the spirit of Professor Christian Wolff, who found in the whole universe nothing more worthy of praise than the fact that it serves the usefulness of man.

Lambert's book was rendered into popular French by the philosopher Jean Henri Samuel Formey, and in 1797 it appeared in Russia under the title *The System of the World of the Celebrated Lambert*.

Well known to his contemporaries, Lambert's system of the world was largely forgotten in the nineteenth century. Only in our own time has the idea of the structural infinity of the universe — first advanced more than two hundred years ago by Johann Heinrich Lambert — once again attracted the attention of cosmologists.

But that belongs to a later discussion...

4.6 Wilhelm Friedrich (William) Herschel

In 1784 the king of English astronomers, William Herschel, became absorbed by the idea of determining the structure of the universe. Before him, this problem had been approached more than once, but always on the basis of a priori speculation. The ideas of Emanuel Swedenborg, Thomas Wright, Immanuel Kant and Johann Heinrich Lambert were typical examples of "hypotheses from the ceiling". Herschel resolved to place the search upon what he regarded as the firm scientific ground of observation.

Dividing the sky into sections, he began counting the bright points, sampling first one region and then another. It turned out that the number of stars indeed increases markedly in only one direction — towards the Milky Way. The speculative hypotheses of his predecessors thus received a certain confirmation.

Herschel then declared that the number of stars in the universe is far from infinite. All stars, he suggested, are most likely gathered into a single vast system resembling in shape a lens or a flattened disc. Therefore, if one observes from near the centre of such a system along its greater radius, one will see nearby stars clearly; beyond them, more distant stars less distinctly; and farther still, an accumulation of remote and most remote luminaries appearing only as a faint mist — the Milky Way. If one turns one's gaze away from the great radius, the number of visible stars should steadily diminish.

The conclusion seemed almost inevitable: there exists a single enormous stellar system. Herschel called it the Galaxy[21] and estimated that it contains about 300 million stars. He calculated the greater radius of the system to be roughly 4,000 light-years and the lesser about 750 light-years. The Sun, in his view, lay not far from the centre of the Galaxy.

[21] From Greek *galaxias* (kuklos) 'milky (vault)', from *gala*, *galakt-* 'milk'. – DM

Herschel cannot be denied either insight or logic. This is all the more remarkable because the profession for which his parents had prepared him from childhood did not at all encourage the development of a strictly logical mind.

William Herschel was born on 15 November 1738 in Hanover, the chief city of the densely populated kingdom of the same name, ruled by English governors. The English kings took a lively interest in this fragment of the continent, scarcely 200 by 200 kilometres in size, and regarded events in Hanover as matters close to their own hearts. Yet, as is wisely observed in a well-known play, it is best when both a master's anger and a master's favour pass one by.

Throughout its independent history Hanover was an unusually restless region. Beginning with the Seven Years' War, the unfortunate kingdom became a recognised meeting place for various armies — and they did not assemble there for parade. At different times the land was occupied by English, Prussians, French, Russians, and Swedes.

These complicated affairs of long ago might scarcely concern us today, were it not that they played a decisive role in the life of the man who interests us here.

The father of the future observer of the stars, Isaac Herschel, was a musician in the Hanoverian Guards and the head of a large family. He played the oboe and from an early age prepared his fourth son, Wilhelm, for a musical career.

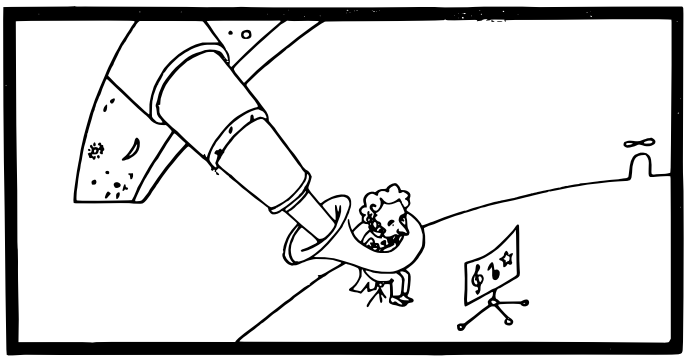
In 1755 the seventeen-year-old musician William Herschel, dressed in the shining uniform of a regiment of the Hanoverian Guard, marched under the English banner along the marshes of East Frisia and the Teutoburg Forest in search of glory. Military service, however, was not among the young man's true callings. After the unfortunate campaign of 1757, and not without the assistance of his devoted father, he deserted from the valiant ranks. It was dangerous to remain at home. In that same year, 1757, a young and energetic musician named William Herschel appeared on the misty shores of Albion.

It was not easy to establish oneself in England. Herschel struggled for existence by every possible means. He trained the regimental band of the Durham militia, gave private music lessons, served as an organist in a chapel, and played the oboe in a private orchestra. He conducted oratorios, organised concerts, composed chorales and sacred songs. At the same time, an insatiable thirst for knowledge drove him to study mathematics and optics, foreign languages and astronomy.

In 1773 he borrowed a small telescope and, turning away from the clavier, looked at the sky. It is said that that evening Herschel was late for a lesson for the first time

in his life and inattentive to his pupil. The purpose of this thirty-five-year-old immigrant's life had been decided.

With the same energy that he had previously devoted to music and theoretical studies, William Herschel now turned to grinding mirrors. He needed a good instrument. For a whole year he learned the craft. One failure followed another. Bound by his musical duties and contracts, he gathered minute after minute for the work. Only on rare free days did he surrender himself entirely to his passion, grinding for sixteen hours without interruption.



His sister Caroline Herschel, whom William had brought from Hanover once his earnings improved, read aloud to him and even fed him as he worked, placing pieces of food into his mouth so that he need not interrupt his labour.

At last, in 1774, the first reflecting telescope was completed, and Herschel began his observations. Reading the

biography of this enthusiast, one is struck by his overflowing energy. Without reducing his musical commitments, he even managed to observe the heavens during concert intervals. In those years no one saw him walk; he always ran — and with remarkable swiftness.

He was in his forty-first year when he published his first paper. Yet, despite beginning scientific work so late, he went on to discover 806 double stars and 2,500 nebulae, and to carry out four complete surveys of the sky. He produced the first systematic classification of the brightest stars according to their luminosity and discovered the planet Uranus. The results of this tireless man's labour would have sufficed for several lifetimes.

At the age of fifty he married a young widow in whom, according to contemporaries, "exceptional moral virtues were united with a considerable fortune." Four years after the marriage a son, John Herschel, was born. After some hesitation he followed his father's path and himself became a distinguished astronomer.

In advancing his hypothesis about the structure of the Galaxy, William Herschel did not challenge the universe of Isaac Newton. No: his lens-shaped, or millstone-like, Galaxy simply hung alone in infinite space, containing within itself all existing stars, planets, comets, and nebulae.

The latter, however, presented greater difficulty. Charles Messier, the French "comet hunter", having mistaken nebulae for the comets so dear to his heart, entered 103 neb-

ulous objects in his catalogue of 1771. Herschel increased their number to 2,500. In 1786 he wrote:

> "I have seen double and triple nebulae in the most varied positions; large with small, resembling satellites; narrow and very long bright nebulae, like shining sprays; some in the form of a fan or an electric brush issuing from a luminous point; others resembling comets with nuclei at the centre; stars surrounded by nebulous envelopes; milky nebulae such as the astonishing and incomprehensible formation near Theta Orionis; finally, nebulous patches shining unevenly, which seemed to indicate their resolvability into stars."

Herschel discovered that certain objects which Messier had taken for nebulae were resolved, in his great telescopes, into clusters of stars. This circumstance troubled him and led him to consider whether the difference between nebulae and star clusters might depend solely upon the resolving power of the telescope.

Overburdened with work, Herschel did not know that this original idea had been expressed half a century earlier, as a speculative hypothesis, by Immanuel Kant. Perhaps it was just as well that he did not know it. Having once paid tribute to the notion of "island universes", Herschel even boasted in conversation that he had discovered fifteen hundred new universes. Yet the English astronomer later adopted a different view, considering those nebulae not resolved into stars to be a "luminous fluid, the nature of which is entirely unknown to us."

Yet even this opinion was not final. For a time, William Herschel thought that the various kinds of star clusters and nebulae were in fact the same objects, merely at different stages of development. In 1789 he wrote:

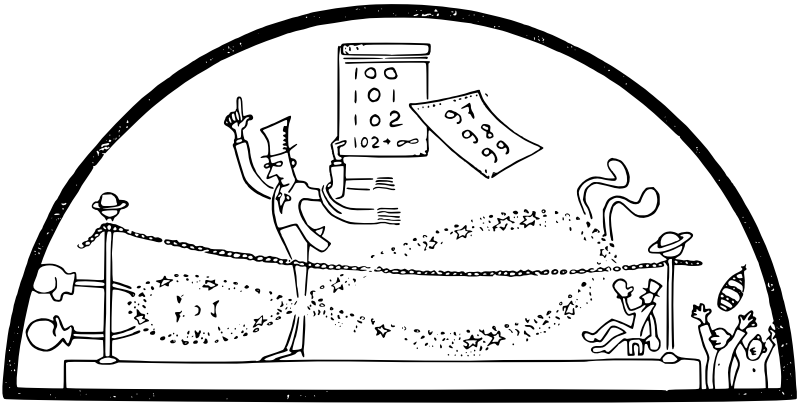
> "The heavens now appear to me as a magnificent garden containing a vast variety of plants, set out in different beds and in various stages of growth... I ask you, is it not the same whether we observe in succession the birth, flowering, leafing, fertilisation, withering, and finally the complete decay of a plant, or whether we contemplate at once a multitude of specimens taken from the different stages through which a plant passes in the course of its life?"

In 1811 and 1814 he even published his own theory of the gradual condensation of a luminous fluid forming a nebula into a star cluster, then into a nebulous star, and finally into an ordinary star or a group of such stars.

Toward the end of his life, Herschel quite radically altered his views even on the structure of the universe and the distribution of stars within it. He returned once more to the idea — if not of an openly infinite universe — then at least of a world consisting of a multitude of stellar systems similar to the Galaxy.

From Herschel's life one may readily see that a person's point of view is not something fixed, rigid, or granted once and for all. On the contrary, it evolves together with the individual and may even change into its opposite. Yet there is one thing a person has no right to abandon — if he wishes to preserve self-respect to the end of his days — and that

is devotion to the pursuit of truth.



5. The Dark Night of the Paradox

In which the idea of Newton's infinite universe encounters its first difficulties and is knocked into a state of near defeat.

So then, the universe is indeed infinite! In the eighteenth century this assertion seemed to no one sensational. The principle had already been proclaimed by the ancient

Greeks. The singer of change, who chose as his motto "Everything flows", Heraclitus was convinced that the universe is infinite in time.

The "laughing philosopher" Democritus considered the universe infinite in space.

Christian preachers confined the space of the world within the crystal sphere of the fixed stars, assigning it a finite span of time from Creation to the Last Judgement. Yet beyond the boundaries of that crystal sphere began the world of God — of which nothing was said openly, but which was secretly imagined as having neither end nor limit.

The Dominican monk Giordano Bruno declared that there is no difference between worlds and that the universe is infinite in space and eternal in time.

Since then, the concepts of the finitude and the infinity of our world have replaced one another with remarkable regularity.

"Infinity" is an uncomfortable word, an uncomfortable notion. Try to imagine infinite space without end or boundary, without bottom or ceiling...

Common sense suggests that space is a place which some object may occupy. So taught the philosophers of antiquity. The universe is the universal space, the container of all things.

Yet even if one persuades oneself that the number of "all

things" is countless, it is still impossible to form a concrete image of infinite space. The very thought of infinity is intolerable to the human mind. It leads into an intellectual dead end.

Then, in 1744, the meticulous Swiss astronomer Jean-Philippe de Cheseaux voiced the first doubt concerning the correctness of Isaac Newton's conception of an infinite universe. Only a doubt — no more. Barely seventeen years had passed since the death of the great physicist, and his fame was dazzling. And yet...

"If the number of stars in the universe is infinite," de Cheseaux reasoned, "why then does the whole sky not blaze like the surface of a single star? Why is the sky dark? Why are the stars separated by black intervals?"

The modest astronomer was himself alarmed by his boldness. To pose such a question meant casting doubt upon Newton's assertions. And de Cheseaux immediately sought worthy objections to his own argument:

"Most likely, clouds of dust obscure from us the light of distant stars. Observers on Earth can receive only the rays of the nearest luminaries..."

The Swiss voice sounded uncertain, almost timid, and for eighty-two years his objection was drowned out by the thunder of praise surrounding the incomparable Newton.

5.1 The First Attack on Newton's Universe — Olbers' Paradox

Heinrich Wilhelm Matthias Olbers was a physician — a good, practising doctor whose patients belonged to the most respectable families of the city of Bremen. A worthy man — Doctor Olbers, without question — but... Heinrich Olbers might have enjoyed even greater esteem among the Bremen burghers had he devoted himself to medicine alone.

To general regret, Doctor Olbers possessed an observatory. Yes, indeed — a private observatory in which he carried out all manner of observations of the heavenly bodies. And what, one might ask, was good about that? What good is it if a physician, instead of sleeping peacefully at night, sits like a sorcerer, staring through a long tube into the starry sky? It does not look proper.

Such behaviour unsettles the ordinary citizen. He does not like it when someone differs too markedly from him — whether in thoughts or in conduct. Even if that someone is a doctor. Even if he is a good doctor.

True, Herr Olbers had one mitigating circumstance. He was wealthy. And therefore Heinrich Wilhelm Matthias Olbers could afford to ignore the tastes of his patients, not to chase after an expanding practice, and instead to devote more time to the stars. It was his hobby, as we would say today.

Incidentally, Herr Olbers was a rather well-known figure in astronomical circles. His fame rested upon the discovery of two minor planets — 2 Pallas and 4 Vesta — and upon a substantial work devoted to a method for calculating cometary orbits. His position allowed him to support young and aspiring observers and, on one occasion, even to help the then little-known mathematician Friedrich Bessel enter the guild of astronomers.

Olbers gave high praise to the young mathematician's work on the reduction of observations of Halley's Comet. In later years Bessel became famous, and Olbers remained proud to the end of his life of the good deed he had managed to perform.

The patient reader may well protest. Our subject, after all, is cosmology — our subject is the universe. In the heading the author promised an "attack" upon the established and observation-tested views of Newton himself. Where is it?

Let us recall that at that time the conception of the universe rested upon three postulates.

I. The universe is boundless and unchanging in time.
II. The number of stars, uniformly distributed in homogeneous space obeying Euclidean geometry, is infinite.
III. All stars have, on average, the same luminosity. Therefore bright stars may be regarded as nearer, and faint ones — more distant.

These three principles yielded an infinite and spatially homogeneous cosmological model of the universe, unchanging in time. Its space unquestionably possessed all the properties of three-dimensional Euclidean geometry — length, height and width — and was entirely independent of the matter contained within it.

The author, borrowing the terminology of Vitaly Ginzburg, will hereafter refer to such a model as the SHE model — that is, stationary, homogeneous and Euclidean.

Around the year 1826 the universe appeared to Olbers as a gigantic cabbage with an infinite number of layers — leaves. On each layer — stars. Relying upon this mental picture, Olbers attempted to calculate the distribution of the stars.

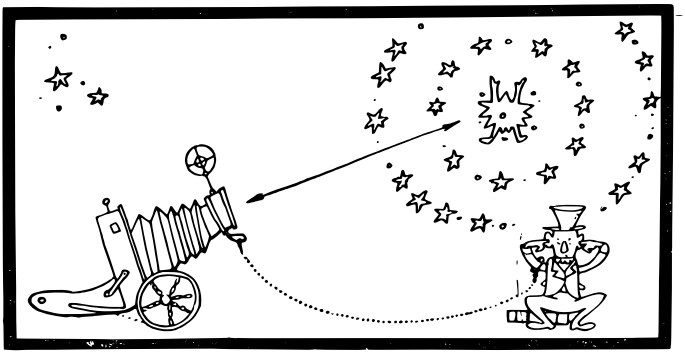
If one accepts all three postulated properties of the Newtonian universe mentioned above, then the surface of each successive "cabbage leaf" — a layer whose radius is twice that of the preceding one — increases as the square, that is, fourfold. And, under the condition of uniform distribution, it contains four times as many stars as the previous layer.

The light of any star is inversely proportional to the square of the distance. Thus the light of stars situated twice as far away appears four times fainter. But if there are four times as many stars?...

It was time for Olbers to reflect. The conclusion was unavoidable: the Earth — if one imagines it as the stalk at

the centre of this cosmic cabbage — would receive from every layer of the universe the same amount of light. And *since the number of layers is infinite, the entire sky, without a single gap, ought to shine like the surface of a single Sun*.

Stop. We have heard similar reasoning before. Was it not advanced by Jean-Philippe de Cheseaux? In order to preserve the authority of Isaac Newton, Cheseaux had been forced to fashion a fig leaf out of cosmic dust clouds.



Olbers went further in his argument. Under a continual avalanche of light, any masses of dust would gradually begin to heat up. They would heat and heat until they became so hot that they themselves would emit as much light as they absorbed. The total amount of light pouring down upon human heads would remain the same.

Thus dust clouds do not rescue the situation. The respectable Olbers was in no haste to invoke Newton's name

in vain. Yet one of the conditions — I, II, or III — had to be false. More precisely, either I or II. For the assumption of equal stellar luminosity had no effect upon Olbers' conclusion. Therefore either the stellar universe is not infinite, or the number of stars within it is in fact limited.

Such a conclusion agreed rather well with the lens-shaped model of the Galaxy proposed by William Herschel.

Olbers' photometric paradox played an almost decisive role in ensuring that, for nearly a whole century, the idea of an infinite universe could not recover from the blow and lay stretched out upon the ring. Yet what is a hundred years to infinity?..

In 1839, in Russia, not far from St. Petersburg, the new Pulkovo Observatory was brought into operation. The construction was directed, and the first directorship held, by Friedrich Georg Wilhelm von Struve — formerly a philology student in Dorpat who had once "caught" astronomy and become a professional observer. Having moved to St. Petersburg, Friedrich Georg Wilhelm adopted the name Vasily Yakovlevich and enriched the science of the stars with a considerable number of brilliant observations.

While studying the laws governing the distribution of stars, Struve arrived at the conclusion that light must inevitably be absorbed by the interstellar medium, and he even calculated the magnitude of this absorption — incidentally, a value fairly close to the modern one.

Struve then demonstrated that our Sun is by no means

situated at the centre of the Galaxy, as Olbers had supposed, but rather nearer its edge. As for the boundaries of this Galaxy, in the Russian astronomer’s view they were so remote that they would never come within the reach of sight. Vasily Yakovlevich Struve firmly maintained that light gradually fades in the interstellar medium and reaches us from distant luminaries in a weakened state.

It must be said that the distinguished astronomer’s position on the structure of the universe was not entirely clear-cut. On the one hand, he cast doubt upon Olbers’ paradox and thereby seemed to lend support to the advocates of an infinite universe. On the other hand, William Herschel’s hypothesis also left him far from indifferent.

5.2 Knights of the “Heat Death”

It can hardly have escaped an observant reader that water in rivers, canals and streams always flows downhill — from a higher level to a lower one, driven by a certain “tendency towards levelling”. Nor would the inhabitants of the far northern latitudes believe you if you were to assure them that in frost one may grow warm by sitting upon an ice floe. Common sense and everyday experience insist that heat is transmitted only from a hotter body to a colder one, thus realising the same “principle of equalisation”.

But what does this much-invoked “equalisation” mean in physical terms? Above all, it signifies the degradation

of energy. For once equilibrium is reached, no processes involving the expenditure of energy can be expected.

In 1850 the twenty-eight-year-old German physicist Rudolf Clausius, then a lecturer in physics at the Zurich Artillery School, reflected upon the simple fact of temperature equalisation and formulated a law that came to be known as the *Second Law of Thermodynamics*. The law stated:

> "Heat cannot of itself pass from a colder body to a hotter body."

A year later, an even younger English physicist, the twenty-six-year-old William Thomson — who forty years afterwards would become the second most prominent figure in the history of British physics — offered a somewhat different formulation of the same law and proposed that the measure of equalisation, or of the degradation of energy, be called *entropy*.

In modern thermodynamics the Second Law is formulated, in its most general form, as the law of the increase of entropy: *in a closed system all processes lead to a growth of entropy*. Of course, we do not mean purely reversible processes, in which entropy remains constant. In nature such ideal processes simply do not occur; they are no more than a useful theoretical abstraction.

In real systems, energy stored in one or several bodies tends to spill out into the surroundings, to spread in an even layer throughout the space of the closed system, to degrade, to become levelled. The very term "entropy",

translated from the Greek, means "turning inward" — not a particularly vivid image.

Let us imagine a closed system of bodies, some of them heated, others cooled. By making use of the temperature difference — which reflects differing amounts of stored energy — we may convert thermal energy into other forms of energy and perform work. Each such act of work will be associated with a lowering of the temperature of those bodies whose thermal energy we have partially used. At the same time, the temperature of the cooler bodies (or of the surrounding medium) will rise. Our system is closed; the energy has nowhere to escape.

But suppose that all forms of energy have been converted into heat, and that all the heat has been distributed uniformly among all the bodies of the closed system. Shall we then be able to perform any work? No. Clearly not. No energy sources remain. The energy has degraded, lost its value, enveloping all bodies in a uniform layer. For the closed system, "heat death" has arrived.

The rigorous reader has long been ready to ask: "What, strictly speaking, has this to do with cosmology?" It is here that the matter becomes most intriguing.

The young William Thomson maintained that the material universe — stars, planets, comets and other celestial bodies — constitutes a single, closed and isolated system. The universe is one; there is no other like it. If that is so, then the Second Law of Thermodynamics applies fully to the entire cosmos. And therefore, in the end, our varied

and lively world must be awaiting a dreary "heat death".

A few years later Rudolf Clausius agreed with Thomson's conclusion, writing:

> " ... the entropy of the universe tends towards a certain maximum. The more the universe approaches this limiting state, ... the more the motives for further change disappear; and if this state were finally reached, no further changes would occur, and the universe would be in a kind of lifeless state of inertia."

The theory of "heat death" stood in glaring contradiction to the Newtonian eternal universe (the model we called the SHE-model). For if the world has existed forever, then all processes within it ought long ago to have subsided, the stars to have gone out, and the clouds of interstellar dust to have warmed slightly. We ourselves, one might argue, would have no right to exist in a world that conforms both to those postulates and to the Second Law of Thermodynamics. Thus the theory of heat death marked a second assault upon Newton's universe.

The theory was eagerly welcomed by theologians, who had not received such a generous gift from science for a long time. If nature cannot by itself escape the thermal impasse, then a deity is required to assist it. This idea has continued to comfort theologians to the present day.

In 1952 Pope Pius XII wrote:

> "The law of entropy, discovered by Rudolf Clausius, has given us the assurance that spontaneous natural

> processes are always linked with a loss of free, usable energy, from which it follows that in a closed system these processes will eventually cease on a macroscopic scale. This sad necessity ... eloquently bears witness to the existence of a Necessary Being."

Three years later the West German theologian Katcher drew an even more explicit comparison between the life of the universe and the workings of a clock. At some moment, he suggested, God wound up this clockwork mechanism; since then the clock has been ticking until the spring runs down. After the complete halt — that is, after "heat death" — perhaps God will wind His "little clock" again.

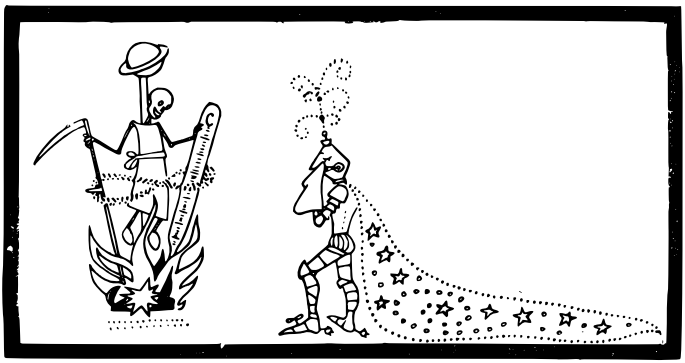
It has never been easy to argue with the "knights of heat death". Not all energy transformations in the universe are fully understood, and this leaves the opponents of Clausius, Thomson and Pius XII in a vulnerable position. Nevertheless, many physicists and philosophers could not reconcile themselves to their conclusions. While recognising the scientific value and correctness of the Second Law of Thermodynamics, they refused to accept the inevitability of heat death.

Nikolay Chernyshevsky wrote: "A formula that foretells the end of motion in the universe contradicts the fact of the existence of motion at the present time. This formula is false."

At the beginning of the twentieth century the well-known Swedish physical chemist Svante Arrhenius, who devoted much attention to the formation and evolution of

celestial bodies, also spoke against heat death.

> "If Clausius were right," he wrote in 1909 in his book *The Making of Worlds*, "then this 'heat death' would already have occurred during the infinitely long existence of the world, which, however, has not happened. Either one must assume that the world has not existed infinitely long and that it had a beginning; yet this contradicts the first part of Clausius's proposition, which states that the energy of the world is constant — for then one would have to admit that all energy arose at the moment of creation."



A remarkable philosophical critique of the idea of heat death is contained in *Dialectics of Nature* by Friedrich Engels. He was the first to point out that the idea contradicts, above all, the principle of the conservation of energy. Engels advanced the hypothesis of a circulation of energy in the universe — the hypothesis that energy is indestructible not only quantitatively but also qualitatively, a view later

supported by the further development of science. He was firmly convinced that Clausius and Thomson had merely raised the question of whether the Second Law of Thermodynamics could be extended to the universe as a whole, rather than having resolved it.

And in this Engels proved right. Before long, the first step in this direction was taken by the Austrian physicist of tragic fate, Ludwig Boltzmann.

During his lifetime he changed more than one university chair. The materialist views of Professor Ludwig Boltzmann were received very unfavourably by many of his colleagues. His principal works were devoted to the kinetic theory of gases and to the statistical interpretation of the Second Law of Thermodynamics.

Confronted with the problem of "heat death", Boltzmann proposed that the universe as a whole exists in a state of thermodynamic equilibrium — that is, from the energetic point of view the world is dead. Yet individual regions of the universe are subject to fluctuations. Our own part of the infinite universe, all the space that can be surveyed by a human observer armed with a telescope, is in the state of an immense fluctuation, now gradually dying away.

This hypothesis completely removed God even from the act of creation. However, it did not abolish the sombre forecast of "heat death". People naively supposed that whether one perishes by the will of God or as the result of the ending of a fluctuation makes little difference. With

God, it somehow felt more familiar.

5.3 Hugo von Seeliger and the Gravitational Paradox

The third assault upon the infinite universe began only five years before the dawn of the twentieth century. One of the most influential German astronomers of the time, Hugo von Seeliger, accepted the idea of an infinite universe and attempted to apply Isaac Newton's law of gravitation to the entire infinite mass of celestial bodies filling the world. He encountered a paradox.

Newton's law, which completely determines the gravitational field for a given distribution of masses in space, led to indeterminacy when one tried to extend it to the whole infinite mass of the universe. The paradox lay in the following: if the universe is infinite, then every particle of matter is acted upon by the resultant of two infinite forces. But the difference of infinities is always indeterminate. Hence the Newtonian universe proves ambiguous, and therefore no laws of nature can be consistently applied to it.

To overcome this difficulty, one had to assume that the density of matter decreases rapidly and without limit with distance. Yet this reduces the conception of an infinite universe with a uniformly distributed stellar population to that of a finite universe.

Having suffered a blow from the very theory of gravitation that formed its foundation, Newtonian cosmology began to waver. The gravitational paradox was perhaps the most serious difficulty faced by Newton's theory of gravitation.

At the risk of testing the reader's patience, one must recall that, in Sir Isaac's own view, a finite universe could not exist. In his correspondence with Bishop Bentley, Newton wrote that if matter were confined within a limited region of space, then by virtue of the mutual attraction of its particles it would eventually gather into a single spherical body. Only because matter is dispersed throughout boundless space can it concentrate not into one body, but into an innumerable multitude of cosmic bodies.

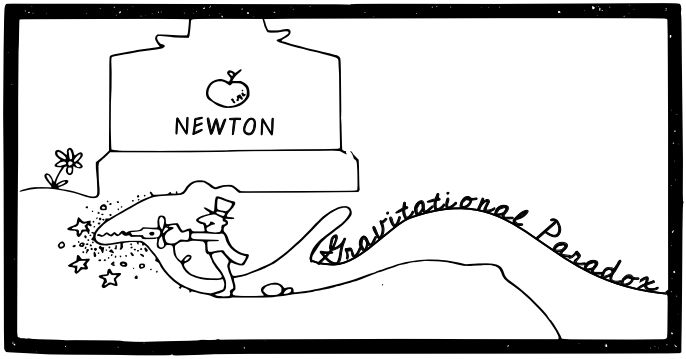
The gravitational paradox caused unease among astronomers and physicists alike. In both camps certain inconsistencies within the general theory began to appear. And yet most scholars believed that the principal scientific problems had been resolved in the nineteenth century.

It was, after all, an astonishingly calm century, filled with complacency and tranquillity.

> "Today one may confidently say that the grand edifice of physics — the science of the most general properties and structure of inanimate matter, of its principal forms of motion — has essentially been completed. Only minor finishing touches remain ..."

So spoke a tall, grey-haired gentleman addressing his colleagues on the eve of the new year 1900. The speaker was

William Thomson, First Baron Kelvin — Sir William, Lord Kelvin, President of the Royal Society of London and a scientist of worldwide renown.



Comfortably settled in their high-backed antique armchairs, the gentlemen nodded in satisfaction. They had done much to earn the right to hear such words bringing the nineteenth century to its close. Tomorrow a new century would begin — a century in which physicists, it seemed, would be left with nothing more than "minor finishing touches" to complete.

That was how the physicists reasoned. The astronomers were not far behind them. The nineteenth century was an age in which science was regarded as a finished sum of knowledge. That sum had already been accumulated; future generations would merely need to tidy a few details, comb and arrange them neatly on their shelves ... including the removal of three minor yet irritating paradoxes

which, in truth, did not prevent astronomers from sleeping soundly on stormy nights. Scholars frowned when recalling the names of Olbers, Clausius and Seeliger.

In physics, too, by 1899 there were a couple of hazy clouds on the horizon. But what were a few unexplained experiments compared with the grand temple of classical physics?..

Then it arrived — that new and mysterious twentieth century. Within five years the "clouds" on the "physical horizon" burst into such flashes of lightning that the suddenly awakened scholars beheld a frightening sight. The temple of science, the majestic edifice of classical physics, proved to be a tiny and pitiful watchman's hut on the building site of a new physics — the physics of relativity and of the atomic nucleus.

It would have been quite unjust if, at the same time, everything in astronomy had remained just as calm as before.

5.4 A Celestial Census Saves the Situation

By the beginning of the nineteenth century, the world of heavenly bodies consisted of stars, planets, comets, asteroids, and "hairy" objects — as the indistinct nebulae, unresolved by any telescope of the time, were then called. By the beginning of the twentieth century, astronomers already knew of roughly thirteen thousand such nebulae.

Had astronomers rummaged through the dust of the archives, they would have come upon the forgotten hypothesis of Immanuel Kant, who in 1755 suggested that nebulae were gigantic clusters of stars located at enormous distances from us. Kant even called them "island universes". Yet, unfortunately, at that time no stars could be discerned within the nebulae, even through the finest telescopes.

True, once — around 1845 — the Irish aristocrat William Parsons, better known as Lord Rosse and an enthusiastic builder of telescopes, caused quite a commotion one night. Seated in his private observatory beside the largest telescope in the world, constructed in the workshops of Birr Castle (the Parsons family estate), Rosse detected a remarkable fibrous structure in the Andromeda Galaxy. The eccentric lord, shouting loudly, woke the household and summoned them to behold the unprecedented spectacle. In the field of view of the giant telescope, the pale streams of distant Andromeda seemed to twist like a whirlwind into a vast spiral.

Having thus opened up a new class of celestial objects — the spiral nebulae — and having received the approval of the Royal Society, Lord Rosse grew calm once more.

Forty years later, the Andromeda nebula drew attention once again. A star flared up in the centre of the spiral cloud. The more cautious observers suggested that the star might have ignited somewhere between the nebula and the Earth. The bolder ones recalled the hypothesis

of Immanuel Kant. Yet no one was able to discern other stars within the nebula. What was needed was either a new telescope — or something else.

This second possibility was a new method for studying distant celestial objects. It was called *spectral analysis*. This allowed one to determine the chemical composition of heated matter from the colours of its spectrum.[22]

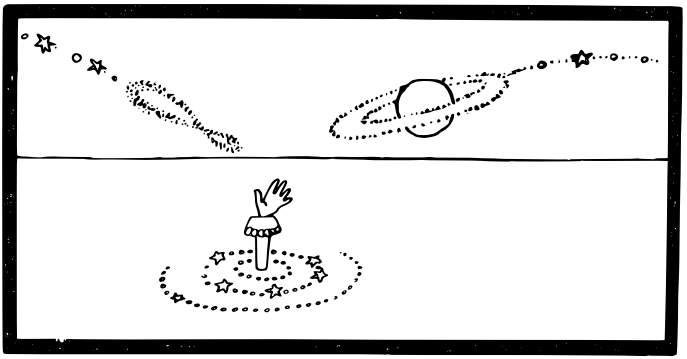
Astronomers quickly adopted spectral analysis. They applied it first to stars, and then to nebulae. If the spectrum of the Andromeda Galaxy, obtained in 1899, had consisted of separate bright lines, the problem would have been solved at once. Discrete lines indicate hot gas. However, the spectrum of the mysterious nebula proved to be continuous and faintly white. This suggested that the nebula might in fact consist of a multitude of stars separated from us by an enormous distance. On the other hand, cold gas reflecting starlight can also produce a continuous spectrum.

Thus, despite the absence of direct proof, the view that nebulae were clusters of stars gradually gained strength. People began to suggest that they were galaxies like our Milky Way, and that the universe was filled with them more or less uniformly. This once again supported the Newton–Kant conception of an infinite universe populated by an innumerable host of stars. True, the paradoxes of Olbers and Seeliger continued to protest against such a picture.

Contradictions exist in order to be resolved. Thus the German astrophysicist Robert Emden formulated the con-

[22] A spectrum is the range of colours (or wavelengths) produced when light is dispersed, for example through a prism. Each element produces a unique pattern of bright or dark lines at specific wavelengths, acting like a "fingerprint". By matching these patterns, spectral analysis allows the chemical composition of a substance to be identified. – DM

ditions for the equilibrium of a gaseous sphere, intending to build upon them a theory of stellar formation. He succeeded. He found such a structure, such a distribution of mass for a sphere of infinite radius and equally infinite total mass, in which the gravitational paradox did not arise. Consequently, the model of an infinite universe once again acquired the right to exist.



Yet this was only a special case. The slightest deviation from Emden's strict distribution caused his elaborate construction to collapse. Moreover, the German scholar's sphere possessed a centre. But how is one to find a centre in an infinite universe?

After him, the Swedish scientist Carl Charlier — professor at the University of Lund and director of the observatory there — undertook to rescue the infinite universe. Studying the spatial distribution of stars, Charlier applied new methods of mathematical statistics and by about 1908

developed his own foundations for a theory of the structure of the universe. Within his subtle and ingenious mathematical schemes there appeared structures without a centre, yet obedient to Newton's law and free from both the gravitational and the photometric paradoxes.

Neither Emden's spheres nor Charlier's refined mathematical constructions proved a revelation. To eliminate the paradoxes, something more fundamental had to be altered. Preferably, the change should concern the very assumptions underlying the model of the universe itself.

As Academician Vitaly Ginzburg wrote:

> "To introduce changes into a theory, especially one as fundamental as Newton's, one must have some guiding star — one must rely upon a more general theory or upon new observations. In pre-Einsteinian cosmology such a guiding star was not found."

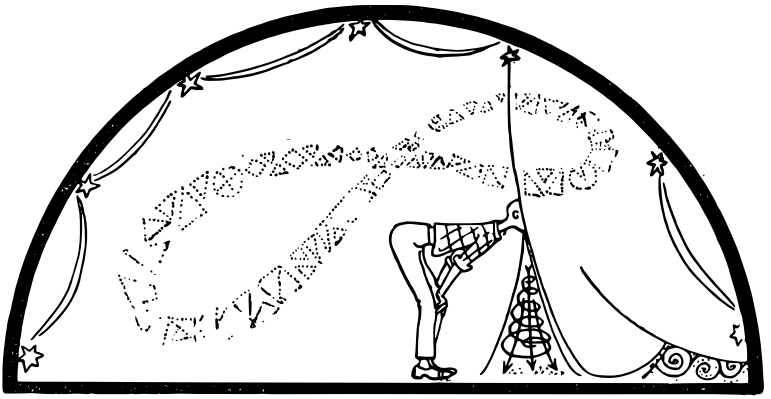
There were, however, attempts. One may recall the efforts made in the nineteenth century to resolve the gravitational paradox. At that time the idea arose that Newton's law of gravitation might be valid only on relatively small, 'terrestrial' scales of the observable universe. In the vast expanses of the greater cosmos, an exponential factor containing a sufficiently small cosmological constant ought to be added to Newton's law.

In that case, for any finite distance the difference between the strictly Newtonian law and the modified version would be negligible. Yet once one passes to infinite space uniformly filled with matter, the difficulties associated with

the gravitational paradox would disappear.

It is curious that no terrestrial experiment — even the most refined — would be capable of detecting such a deviation from the Newtonian formulation of the law of universal gravitation.

Today we understand that adjusting a solution to fit a desired result is a familiar exercise from schooldays, yet one that carries an unmistakable scent of speculation. But in the desperate position in which cosmology found itself at the close of the nineteenth century, almost any expedient seemed permissible.



6. The Copernicus of Curves

In which the reader unexpectedly finds himself in the abstract world of the science of space — so unlike good old geometry, parading in its "Pythagorean trousers" and deftly juggling cubes, cylinders, spheres and cones, as well as all manner of truncated pyramids and polyhedra.

The assaults that were undermining the foundations of the infinite universe were conducted not only by astronomers, but also by mathematicians — although neither group set out with so unworthy an intention.

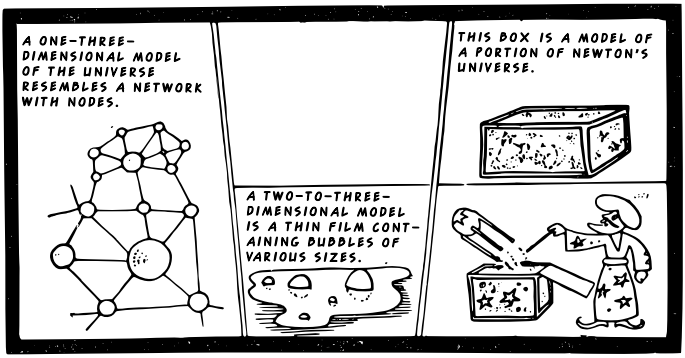
The space of the Newtonian universe existed independently of matter. By "matter" was meant substance distributed in space in one way or another. Substance was the concern of physics, astronomy and other sciences charged with studying the "material" world. Space itself was the province of mathematics and philosophy. From the practical tasks of human activity there even arose a special branch of mathematics — geometry. In the course of its development, it gradually transformed from a practical surveying art into an abstract mathematical theory.

Everything that surrounds us in the world, every object, possesses three dimensions: length, width and height. Any adult can verify this either by sight or by touch, as he prefers. The word "adult" is emphasised because, for an infant, perceived space is two-dimensional. The child does not understand what "far" or "near" means; he stretches out his little hands equally towards his mother's nose and towards the stars.

Yet gradually psychophysiological mechanisms and the accumulated historical experience of humanity — what we call common sense — lead the child to the awareness that the world in which he lives is three-dimensional.

But what is the historical experience of humanity? A few thousand years of conscious accumulation of knowledge.

During that time mankind has spanned distances from the interatomic horizon to cosmological expanses. Colossal — from the human point of view. Yet if one assumes the universe to be infinite, then the portion encompassed by our observations is infinitely small. On what grounds, then, are we entitled to extend so negligible an experience to that which has no measure?


A ONE-THREE-DIMENSIONAL MODEL OF THE UNIVERSE RESEMBLES A NETWORK WITH NODES.
A TWO-TO-THREE-DIMENSIONAL MODEL IS A THIN FILM CONTAINING BUBBLES OF VARIOUS SIZES.
THIS BOX IS A MODEL OF A PORTION OF NEWTON'S UNIVERSE.

Why not suppose, for example, that our universe is one–three-dimensional? Its model would resemble a network with nodes. Each node would be a three-dimensional metagalaxy containing myriads of stellar islands. Look at the drawing. Such a one–three-dimensional model of the universe was depicted by Doctor of Philosophy E. Kolman in his book *The Fourth Dimension*. Beside it stands a model of a two–three-dimensional universe — a thin two-dimensional film with three-dimensional bubbles, the metagalaxies.[23]

[23] E. Kolman refers to Ernst Kolman, a Soviet-era mathematician and Marxist philosopher who earned a Doctor of Philosophy degree and wrote on topics blending mathematics, philosophy, and cosmology. The book *The Fourth Dimension* is his 1970 Russian publication *Chetvertoe izmerenie*, published by Nauka in Moscow, which explores

You may say: fantasy. Very well, I agree. But the model of the Newtonian universe — a vast empty box, space uniformly filled with a thin broth of matter — how is it superior? Merely because it is easier to imagine, relying on experience and common sense?

These two "whales" — experience and common sense — made it possible even in remote antiquity to construct a theory of abstract space and to identify its fundamental properties. The scattered fragments of wisdom were gathered and forged into the "golden rose" of theory by the remarkable Alexandrian mathematician Euclid.

6.1 What Euclid Taught

Euclid drew his diagrams in the sand, on wax tablets, on papyrus scrolls. Not a single reliable line about his life has survived in the archives of history. It is known only that he lived around the beginning of the third century BC, during the reign of the first king of the Ptolemaic dynasty, and that his work was carried out in Alexandria.

One legend, however, has endured. King Ptolemy, to whom Euclid was teaching the elements of mathematics, once complained about the length and difficulty of the introduction to the science. Wrapping his toga about him, the teacher replied that there is no "royal road" to geometry. The path to the heights of knowledge is the same for all mortals, and it begins with simple notions.

The thirteen books of his *Elements*, containing expositions of plane geometry, solid geometry and certain questions of number theory, served for two thousand years as the foundation of mathematical study.

> "In the history of the Western world," writes the mathematician Dirk Jan Struik, "the *Elements*, after the Bible, is probably the most frequently published and most studied book. After the invention of printing, more than a thousand editions appeared, and before that the book, chiefly in manuscript form, was the principal text for the study of geometry. Much of our school geometry is often taken almost word for word from the first six books of the *Elements*, and the tradition of Euclid still weighs upon our elementary instruction."

How did Euclid construct the unshakeable edifice of his geometry? At the foundation of the whole science he placed several fundamental propositions — truths which, for one reason or another, require no proof. The keen Greek philosophers, trained in debate and endowed with a sceptical cast of mind, selected them with great caution. They divided such truths into axioms and postulates.

In those distant times axioms were statements that could not be denied without undermining the very basis of logical thought. When speaking of an axiom, the Greeks would begin with the words: "It is evident that..." — and by doing so they dismissed any further argument on the matter.

Postulates, in the ancient Greek understanding, were

specific statements belonging to a particular science. The opening phrase of a postulate was to begin with the words "let it be assumed that...". This too removed the possibility of dispute, yet it did not impose upon the proposition the character of absolute necessity.

In time, this very important and subtle distinction between axiom and postulate was blurred, and this confusion brought innumerable difficulties both to pure philosophers and to representatives of natural philosophy — but that is a matter for later discussion.

The exposition of geometry in Euclid's books is constructed as a system of definitions, axioms and postulates, from which theorems are derived by logical reasoning. In the first four books he deals with plane geometry. In the first book he formulates five fundamental postulates, or assumptions, upon which he builds all further conclusions.

Euclid's postulates are so visual, so apparently self-evident, that one is tempted to call them axioms. Yet we have already been warned. And we remain alert. Indeed, the postulates themselves, for all their clarity, seem to call for vigilance. See for yourself. Euclid writes:

"It is required" (recall that this is equivalent to saying "let it be assumed that..."):

1. That a straight line can be drawn from any point to any point (and only one).
2. That a finite straight line can be extended continuously in a straight line.

3. That a circle can be described with any centre and any radius.
4. That all right angles are equal to one another.
5. That if a straight line, falling upon two straight lines, makes the interior angles on the same side less than two right angles taken together, then the two straight lines, if produced indefinitely, meet on that side on which the angles are less than two right angles."

Even a reader unversed in mathematics will at once notice that the fifth postulate differs sharply from the first four. It is far more complex and resembles a theorem that ought to be proved. In it there is none of the immediate clarity of the earlier postulates, for it speaks of the "indefinite extension" of straight lines. But try to carry out such an "indefinite extension". Who would dare to assert that, at infinity, parallel lines will not meet?

Intuitively, of course, the fifth postulate appears indisputable. Yet intuition is guided by experience — and experience is powerless before infinity. Most likely Euclid himself understood that all was not entirely secure with the fifth postulate. That is why he divided the material of his books into two unequal parts.

In the first part are grouped the theorems that can be proved using only the initial four postulates. This part is called *Absolute Geometry*. In the second are collected the theorems that can be established only with the aid of the fifth postulate. This second part bears the name of *Euclidean geometry* proper.

It is quite possible that the fifth postulate was once a theorem. Yet none of the attempts to prove it succeeded. And so Euclid included the stubborn theorem among the postulates.

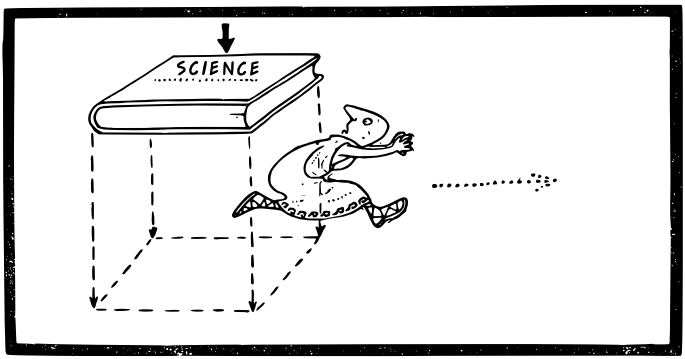
Mathematicians were not so ready to accept his decision.

> "In mathematics there are few matters," wrote Carl Friedrich Gauss, "about which so much has been written as about the gap at the beginning of geometry in the foundation of the theory of parallel lines. Hardly a year passes without a new attempt to fill this gap. And yet, if we are to speak honestly and openly, we must admit that in essence, after two thousand years, we have not advanced any further in this question than Euclid."

From plane geometry, Euclid passes in the final three books to geometry in space — solid geometry. What, then, did Euclid mean by space?

You are holding a book in your hands. Consider it a plane. Now lift it flat above the table and lower it again. The volume through which the book has moved is Euclidean space. Simple, is it not? In this space all Euclid's postulates and axioms must hold, for they constitute its properties. And who would think of doubting, for example, that a straight line may be extended indefinitely? Or that space possesses the same properties everywhere, allowing figures to be moved freely without disturbing their internal relations?

From the abstract geometric notion of Euclidean space it is an easy step to the physical space in which we live and move. And by applying to Euclid's world the visual apparatus of Cartesian coordinates, we achieve a complete fusion of two geometries: Euclid's geometry and the geometry of the physical world.



Indeed, perhaps too easily the notions of geometry — point, line, figure, body — are identified with observable objects. Although a geometric point is an idealisation of a physical point, it seems that such an idealisation cannot possibly undermine the foundations of geometry. The geometric objects of the physical world appeared so identical with those of pure geometry that from this apparent identity arose the conviction that no geometry other than Euclid's could even formally be constructed to describe physical space. In other words, Euclidean geometry was regarded as the only possible geometry of the physical

world.

An attentive reader will have noticed a small logical somersault that turned the relationship between Euclid's geometry and the real world upside down. Born and originally existing as a preface to physics, geometry abstracted spatial forms and relations entirely from their material content and became a branch of pure mathematics. It did so only to substitute itself later for the very system of views describing the real world. This was all the more dangerous because Euclidean geometry, though derived from experience and founded upon axioms and postulates, took no interest in testing its conclusions against experience.

Such metamorphoses are not uncommon in the history of science. Euclid's method closely resembled that of Aristotle. Aristotle likewise postulated a whole series of properties of forces and of their action upon bodies in motion. It required Galileo Galilei for the question of experimental verification to arise. Once that step was taken, the seemingly perfect logical scheme of the philosopher from Stagira — and the mechanics constructed upon it — proved to be simply incorrect. By means of experiment Galileo refuted Aristotle and opened the way to new laws of mechanics.

Something similar was destined to occur with Euclid's geometry. Yet only at the end of the nineteenth century did people realise that the propositions of geometry describing the properties of physical space could — and indeed must — be tested by experience, just like any other laws of physics.

That realisation was a discovery of great importance.

6.2 The King Midas of the Land of Mathematics

Carl Friedrich Gauss was born in Brunswick on 30 April 1777, in the family of a prosperous master plumber. From an early age the boy astonished adults with his gift for calculation. A legend has even survived that, at the age of three, he corrected his father's mistake in settling accounts with his assistants. It is reasonable to suppose that precisely these abilities brought the young heir of a respectable craftsman to the University of Göttingen.

There the student Gauss devoted himself with great thoroughness to the study of mathematics. Euclid's geometry captivated him. Like many before and after him, Gauss expended much effort in the ambitious attempt to prove the fifth postulate. Unlike others, however, he soon became convinced of the fundamental impossibility of proving it.

At the same time an astonishing fact emerged: the fifth postulate was so independent of the others that, by replacing it with a different assumption, one could construct a coherent system — perhaps unlike Euclid's, yet equally free of contradiction. Even the supposition that the fifth postulate might be false did not conflict with the remaining four.

No, the young Gauss did not succeed in transforming Euclid's fifth postulate into a theorem. Yet the attempt gave him a profound knowledge of the foundations of geometry and instilled in him a lifelong devotion to this exact science.

Concerned for his authority as the foremost mathematician of his age, Gauss never again publicly returned to the fifth postulate. Nevertheless, he retained throughout his life a keen interest in it and a certain jealousy regarding the work of other mathematicians who ventured into that field.

Since the time of Euclid, the height of geometrical skill had been considered the construction, using only compass and straightedge, of a regular pentagon, from which — by multiplying its sides — one might obtain a decagon, a fifteen-gon, and so forth. As a student, Gauss discovered a method for constructing a regular seventeen-gon. Five years after leaving the university he published his great work, *Disquisitiones Arithmeticae*. In the final section he presented a fully developed theory of the division of the circle. From that moment mathematicians could construct a wide class of regular polygons without boasting of their virtuosity.

On the eve of the new nineteenth century, on New Year's night itself, the Theatine abbot and founder of the astronomical observatory at Palermo in Sicily, Giuseppe Piazzi, discovered the first minor planet in the "empty" space between Mars and Jupiter. In honour of the goddess of fertility — the patroness of Sicily — he named it Ceres and

reported the discovery to the observatories of Milan and Berlin.

Unexpectedly, Piazzi fell ill and for a long time was unable to approach his telescope. Meanwhile, Napoleonic wars were raging across the European continent. Italy was flooded with armies, and the astronomer's letters travelled at a tortoise's pace. When they finally reached their destination, astronomers searched the starry fields in vain. The newly discovered planet was nowhere to be seen. It had entered conjunction with the Sun and was hopelessly lost in its rays.

Piazzi possessed only observations covering a small arc of a few degrees. However hard he struggled to determine the entire orbit from such scant data, he failed. Every predicted position proved incorrect. Ceres seemed irretrievably lost.

At that point Carl Friedrich Gauss, then an obscure Privatdozent at Brunswick, took up the problem. He devised a new and precise method for calculating the orbit of a celestial body from only three observations and indicated where the vanished planet should be found. The New Year's story received a fitting conclusion: following Gauss's instructions, Ceres was rediscovered on the last night of 1801. Gauss's name became widely known.

Yet the position of Privatdozent weighed heavily upon the mathematical genius. It brought him only eight thalers a month — enough to avoid starvation, but too little to pursue science without constant concern for his livelihood.

He sought a way out. The St. Petersburg academician Nikolai Fuss, with whom Gauss corresponded, proposed that he move to Russia. There he was promised a post as astronomer and director of an observatory, with accommodation and a salary of one thousand roubles a year. Fuss guaranteed his election as a full member of the Imperial Academy and further improvements in his circumstances.

Gauss resolved to go. By chance, the Duke of Brunswick learned of his decision. With a generous gesture he offered the mathematician an annual salary of four hundred thalers on condition that he remain in his homeland. After carefully weighing the advantages and disadvantages, the practical Gauss stayed in Brunswick.

In 1802 a second minor planet was discovered by Gauss's close friend, the physician and amateur astronomer Heinrich Wilhelm Matthias Olbers. He named it Pallas, after the daughter of Zeus — Athena.[24] Once again Carl Friedrich Gauss calculated its orbit using his own method.

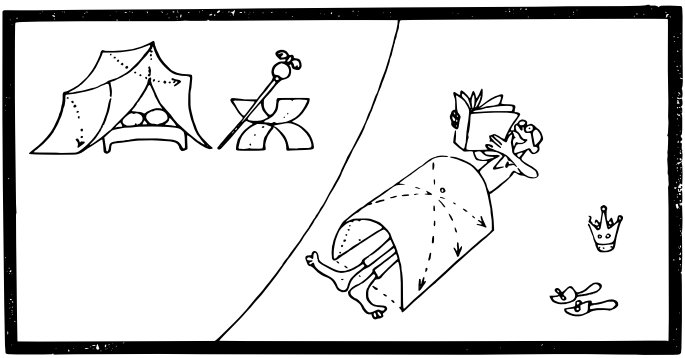
[24] The name Pallas here refers to Athena, who was often called Pallas Athena in Greek mythology. Although a separate figure named Pallas (the Titan) exists, the asteroid's name follows the convention of honouring Olympian deities, and thus refers to Athena. – DM

The results of these investigations, worked out with scrupulous precision, appeared in 1809 in his treatise *Theoria Motus Corporum Coelestium* ("Theory of the Motion of Celestial Bodies"). This work brought the young mathematician worldwide fame. From 1807 Gauss was a member of the Göttingen Scientific Society. In the same year he received the chair of mathematics and astronomy at the University of Göttingen and remained there for the rest of his life.

Only once did he leave Göttingen, travelling to Berlin

at the persistent invitation of Alexander von Humboldt to attend a congress of natural scientists.

Germany in those years was an extraordinary collection of nearly three hundred tiny states. Each had its own duke; each had its own laws. In these miniature realms, whose rulers strained to resemble genuine kings and emperors, there reigned a notably stagnant atmosphere. Yet at every court — or petty court — there was invariably an academy of sciences, and invariably "their own" geniuses maintained for prestige and display, supported by the generosity of the sovereign.



Some rebelled, as Ludwig van Beethoven did at the court of Prince Lichnowsky in Vienna. Others manoeuvred cautiously, striving to realise their ideals without entering into open conflict with their social environment, as Heinrich Heine did in Weimar. Still others valued the security of patronage, fearing the uncertainty of freedom, unwilling

to lose a protector and the familiar conditions necessary for the one great purpose of their lives — science. Such was Gauss. Mathematics was his passion; science was his life.

The Dublin mathematician Cornelius Lanczos wrote:

> "Gauss resembled in some respects the legendary Greek king Midas. King Midas turned into gold everything he touched. Many of Gauss's discoveries arose from incidental questions put before him. Though such questions were often no more than an unwelcome burden, once Gauss took them up with his characteristic thoroughness and precision, he produced something of exceptional importance."

Mathematics, astronomy, geodesy, physics — in all these fields Carl Friedrich Gauss would begin with a modest, particular problem and end by brilliantly resolving fundamental questions, pushing science further and further forward. It was no accident that his contemporaries called him "the foremost mathematician in the world".

In 1820 Gauss received instructions from the minister of public affairs of the Kingdom of Hanover to head the geodetic survey of the state and to compile a detailed map for the demarcation and precise determination of land boundaries. He was by no means delighted with these new duties. Yet he designed a special instrument — the heliotrope — to improve optical signalling; he refined the method of least squares for determining lengths, coordinates, arcs and other quantities in astronomy and geodesy.

Becoming interested in the shape of the Earth's surface, he deepened the general method for investigating curved surfaces. In the end, by opening an entirely new direction in geometry, he created a mathematical apparatus without which the general theory of relativity could not have arisen. It was precisely Gauss's geometric methods that served as a starting point for Albert Einstein in his reflections on general systems of reference.

Since the general theory of relativity forms the daily bread of modern cosmology, the patient reader will understand the need to examine Gauss's geometric discovery more closely.

In studying the measurement of curved surfaces, Gauss was the first to consider their "internal" or "intrinsic" properties — those depending solely upon the surfaces themselves. It was as though he attempted to enter the mental world of a flat, two-dimensional being living upon such a surface. This entirely new perspective effectively created a new "intrinsic geometry" of surfaces.

6.3 Visiting the Flatfolk

The fundamental elements of geometry have always been straight lines and angles. Without them geometry cannot be constructed, just as spelling rules cannot be devised without letters. But can one speak of the existence of straight lines, for example, on a curved surface?

"Of course not," the superficial reader will say. The more thoughtful one will hesitate. Yet let us ask an inhabitant of such a flattened world. We have agreed that on a curved surface there live flat beings, as though cut from a sheet of plastic.

Question. Do straight lines exist in your curved world?

Answer. Why not? If a straight line is the shortest distance between two points, then by moving — or, as you might say, crawling — in one direction, do we not travel along a straight line?

It is difficult to object to this. Do we not, inhabitants of the spherical — that is, curved — surface of the Earth, build "arrow-straight" roads and determine the shortest distances between two cities in precisely this way?

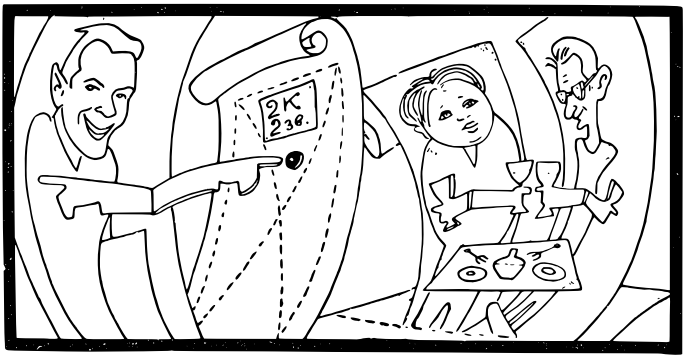
If straight lines exist on a curved surface, then there must also be angles, triangles, circles, ellipses — though their properties may differ from those we are accustomed to in the flat world of Euclid.

In short, the inhabitants of a curved flat world are fully entitled to expect from their own "flattened Euclid" a science no worse than plane geometry.

Now let us imagine that this curved surface closes upon itself to form a sphere. If its inhabitants are sufficiently small in comparison with the radius of the sphere, they simply do not notice the curvature. Incidentally, curvature is an extremely important geometric concept. It is defined as the quantity inversely proportional to the ra-

dius of curvature of the surface at a given point. In a sphere the curvature is the same everywhere. Having realised this, one is tempted — in the best tradition of the ancient Greeks — to frame an axiom beginning with the familiar words: "It is evident that the greater the radius, the smaller the curvature." Admirable.

Let us return to our "flattened" thinkers living on the surface of a vast sphere, unaware of the fact. Their geometry differs in no respect from Euclid's. They will likewise maintain that straight lines are infinite, that triangles are similar, and that parallel lines never meet.



Now imagine that we enter this flat world ourselves. We too must be flattened. You do not object? Even in this unusual condition we remain intellectual giants. Upon the spherical surface — which the local scholars call a plane — we construct a triangle and propose that its angles be measured. The flat geometers measure them: approximately

180°, within the limits of error.

Then we pull the sides apart, stretching the triangle across half the world — that is, across half the sphere. The flatfolk measure again and discover... Well, we of course knew from the outset that in a curvilinear triangle the sum of the angles is not equal to 180°, and so we are not surprised by the result.

Thus, on the surface of a sphere the sum of the angles of a triangle proves to be greater than two right angles — greater than 180°. Let us attempt another test, this time of the first postulate: "From any point to any point a straight line can be drawn (and only one)."

But on a sphere the "straight lines" are arcs of great circles — meridians. From pole to pole, for example, one may draw not one but infinitely many such lines. Another failure.

The second postulate states: "A finite straight line can be extended continuously in a straight line." Let us set off on a journey around the world, keeping strictly to one direction. We travel round the spherical world and return to our own footprints. Evidently Euclid's laws are not applicable to the sphere. The sphere demands a different, non-Euclidean geometry.

An example of this kind once caused Carl Friedrich Gauss to reflect deeply. What, then, of our own world? Do Euclid's plausible yet unproved postulates truly reflect objective reality? Or might the genuine laws of the geometry

of our physical world be altogether different?

For the first time, geometry itself required experimental verification. Gauss did not intend to overthrow Euclid's system as Galileo Galilei had once overturned the views of Aristotle. His temperament was not of that kind. Yet he served truth faithfully, and truth demanded testing.

Quietly, taking advantage of the angular measuring instruments at his disposal for topographical work, Gauss selected the summits of three mountains clearly visible on the horizon: Hoher Hagen, Inselsberg, and the famous Brocken — reputed in folklore to be a gathering place of witches. These peaks formed a suitably large triangle. Gauss measured its angles with all the precision his instruments allowed. He measured, calculated, measured again.

No — the sum of the angles showed no deviation from 180°. Disappointment?

Certainly there was disappointment. Yet Carl Friedrich Gauss spoke of it to no one. He did not fully trust his own intuition and, in letters to friends, would at times express doubts about Euclid, only later to accept his views once more without reservation.

In the end Gauss abandoned reliance upon postulates, replacing them with fundamental quantities that could be measured precisely at each point of a surface by means of the *curvilinear coordinates* (now called Gaussian) he devised. These measurements, taken in themselves, yield the curvature of a surface independently of the space in

which that surface is embedded.

Ordinarily, we judge the form of a surface from outside, holding it in our hands or seeing it before us. A sheet of paper lying on the table is a plane. A roll of linoleum has a cylindrical surface. How do we convince ourselves that the Earth is a sphere? When you observe the night sky in St. Petersburg, the Pole Star stands high above the horizon. Travel south for several hours, and you will see how markedly it sinks towards the horizon. Or watch a ship leaving the shore: first the hull disappears, then the funnels, and finally the masts. The Earth is round.

This is what is called *external curvature* — curvature perceived from the surrounding space, characterised by the familiar radius of curvature.

But what if we possess no information about any external space? Recall that we agreed to flatten ourselves and live upon the surface. There must then exist, alongside external curvature, an internal curvature — one that characterises the surface through its own intrinsic properties. Such a description is less intuitive, yet it is obtained entirely through measurements carried out on the surface itself.

The most complete characterisation of a surface is given by what is called its *total*, or *Gaussian*, curvature. Here we approach the remarkable discovery that Gauss made in his study of curved surfaces.

6.4 Gauss's "Magnificent Theorem"

Let us recall how geometers usually characterise the curvature of a curved surface in the neighbourhood of a chosen point *M*.

First, they construct the plane tangent to the surface at the point under investigation and erect a perpendicular to it. Then they pass through this perpendicular a family of secant planes. Each such plane intersects the surface in a curve which, near the point *M*, may be regarded as part of a circle of greater or smaller radius.

It turns out that the circles with the largest and the smallest radii always lie in mutually perpendicular sectional planes. Geometers take the reciprocals of these radii — they are called the *principal radii of curvature* — and multiply them:

$$K = \frac{1}{R_{\max}} \cdot \frac{1}{R_{\min}},$$

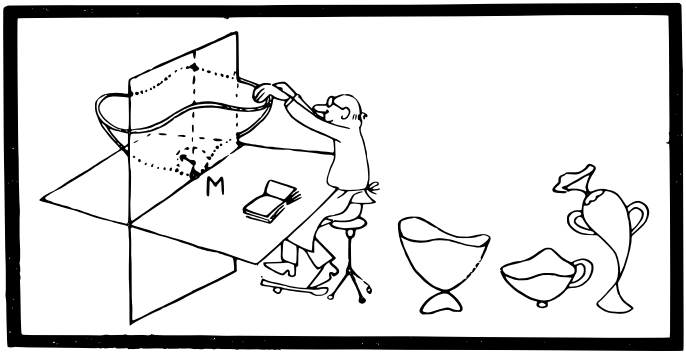
or equivalently,

$$K = \frac{1}{R_{\max} R_{\min}}.$$

The quantity *K* obtained in this way is called the total, or *Gaussian, curvature*.

From the point of view of two-dimensional inhabitants of the curved surface, however, the tangent plane, the perpendicular to it, the secant planes — everything that lies beyond the limits of their two-dimensional world — would

be inaccessible to understanding. For them such constructions would be mere illusion.



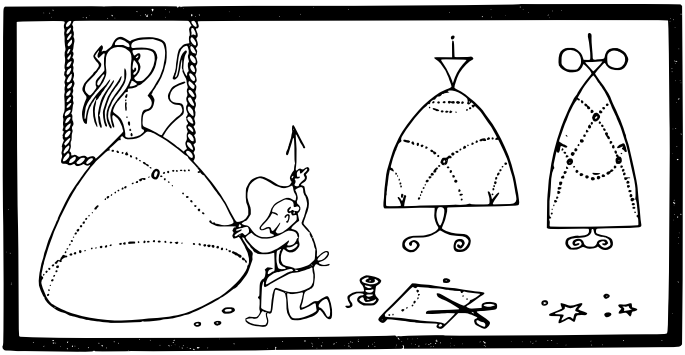
Gauss proved that the total curvature can be expressed, without any auxiliary constructions, entirely through measurements performed on the surface itself — independently of the surrounding external space. This discovery became known as the "magnificent theorem."

Beautiful, is it not? Our predecessors took pleasure in presenting their achievements with elegance. They both loved and knew how to do so — one must grant them that.

The greatness of Gauss's theorem lies in the fact that the *total curvature completely characterises the surface at the point under investigation.* It is accessible to the inhabitants of a two-dimensional world and determines the geometry they must apply.

The flatfolk may have no notion at all of what the "cur-

vature" of their own world means. Yet if, by measurement, they obtain the abstract quantity of Gaussian curvature equal to zero, $K = 0$ they must use the simplest type of geometry — Euclidean geometry.



If, however, the number $K > 0$ is the same at every point of the surface, then a number of Euclid's postulates lose their validity, and one must apply the laws of a different — "spherical" — geometry.

Generally speaking, "internal" and "external" geometry may differ greatly from one another. Consider, for example, three geometric surfaces: the plane, the cylinder, and the cone. Externally they appear entirely different. But what of their internal nature?

Let us divide ourselves in two. Let one half of us flatten out and go to live on a plane — say, on the page of this book. Let the other half remain seated, holding the book

before one surviving eye. Now carefully roll the page into a cylinder or into a conical shape and ask our flattened half a few questions.

"Tell me, two-dimensional being, how are things with your geometry?"

"As before. It was Euclidean and remains so."

"Wait — do you not feel any change?"

"No. The Gaussian curvature is still zero."

And our two-dimensional double is quite right. For a flat sheet of paper both radii of curvature, R_1 and R_1, are infinitely large:

$$R_1 = \infty, \qquad R_2 = \infty.$$

Therefore the product of their reciprocals is zero:

$$K = \frac{1}{R_1 R_2} = 0$$

But zero can also arise if only one radius is infinite. Hence both the cylinder and the cone possess an internal geometry indistinguishable from Euclidean geometry on the plane.

It would be quite different if we attempted to transform a flat sheet of paper into a sphere. In practice, this cannot be done without crumpling or tearing the sheet. A sphere is a surface of an entirely different character from a plane, and therefore its internal geometry is not the same. Its

curvature has a positive value rather than zero:

$$K > 0.$$

In fact, Carl Friedrich Gauss laid the foundations of an entirely new geometry based on experience and measurement rather than on postulates. True, his investigations concerned only two-dimensional surfaces. Yet this was a path that would lead mathematicians onto the broad road of generalisation.

6.5 The Copernicus of Geometry

> "What Nicolaus Copernicus was to Claudius Ptolemy, Nikolai Lobachevsky was to Euclid. There is an instructive parallel between Copernicus and Lobachevsky. Copernicus and Lobachevsky were both Slavs by origin. Each brought about a revolution in scientific ideas, and the significance of these revolutions is equally great. The reason for the immense importance of both lies in the fact that they are revolutions in our understanding of the cosmos,"

wrote the young, lively, yet already incurably ill English mathematician William Kingdon Clifford. He wrote this scarcely twenty years after the death of the great Russian geometer.

On 11 February 1826 a meeting of the Physical and Mathematical Section was held at Kazan University. There a

report was delivered by Professor of Mathematics Nikolai Ivanovich Lobachevsky, devoted to the proof of the "theorem on parallels." His colleagues assembled without much enthusiasm on that bleak February day.

At the university they respected the energetic and unfailingly obliging Lobachevsky, who always responded readily to the requests of his colleagues. Who did not remember that it was Nikolai Ivanovich who undertook to lecture on mathematics at all levels when Professor Bartels departed for Derpt (now Tartu)? And when the professor of physics, Bronner, failed to return to Kazan after his leave, Lobachevsky assumed his course as well, simultaneously directing the physics cabinet and overseeing its equipment.

He replaced the astronomer Simonov, who had set sail with the expedition of Fabian Gottlieb von Bellingshausen, and concerned himself with the fate of the university observatory. The library — especially its physical and mathematical section — was Lobachevsky's cherished creation. He was dean of the section and one of the most active members of the building committee supervising the construction of the university's main building.

It was difficult to understand when he found time to engage in scientific research at all.

Some time earlier, Nikolai Lobachevsky had submitted to the council of the department his work entitled *A Concise Exposition of the Principles of Geometry with a Rigorous Proof of the Theorem on Parallels*. Yet neither

Professors Simonov and Kupfer nor Adjunct Brashman hastened to provide a review. Rumours even circulated that Professor Lobachevsky's memoir was beyond the comprehension of a normal mind. His colleagues were already pitying him, as though a moment of eclipse had overtaken him.

And now he stood at the lectern: thick, dark hair, perpetually disordered; the piercing gaze of deeply set grey eyes.

At eighteen Lobachevsky had become a Master at Kazan University. Three years later he was promoted ahead of schedule to adjunct professor, and two years after that he received the chair of pure mathematics and the rank of full professor. In those days people were expected to mature early. A twenty-year-old without profession, education, or occupation was firmly regarded as idle and useless. A century and a half ago there could be no enthusiasm for "belated infantilism," so fashionable a notion in our own time.

Life today may be longer. Yet it is doubtful whether the span allotted by nature for the accomplishment of great deeds has increased in proportion. A long old age is not merely a period of rest, and a grey beard alone confers no right to admonish. Wisdom, like honour, is gathered from youth; fortunate and great is the people whose youth honours its elders. But every distinction must be earned.

> "Gentlemen," began Lobachevsky, "the difficulty of concepts increases as they approach the fundamental truths of nature... Euclid's *Elements*, despite all our

> brilliant successes in mathematics, have preserved to this day their primitive defects..."

How much he must have pondered before daring to declare this from the rostrum — how much labour of thought was required before there opened to him that astonishing path: from attempts to prove the fifth postulate of Euclid to the unknown. A path that led him to the discovery of a new world, with a new system of measurement — a new geometry.

> "...To set forth all my investigations in their proper connection would require far too much space and would demand a wholly new presentation of the entire science..."

The line of reasoning of the speaker was indeed exceedingly complex, though strictly logical. Reflecting upon the possibility of proving the fifth postulate of Euclid, Nikolai Lobachevsky asked himself: why not proceed by contradiction?

Suppose we leave the first four postulates untouched and discard the fifth. Or better still, let us reject the fifth postulate and instead require that through a point lying outside a given straight line there may be drawn not one, but an entire family of straight lines parallel to the given one. Upon this new system of axioms let us attempt to construct a new geometry.

Clearly such an undertaking must lead to one of two outcomes:

§ either, if the fifth postulate is in fact a consequence of

the first four, the new system will somewhere arrive at an absurdity, since it is built upon an assumption contradicting that consequence; or,

§ if no logical contradiction appears within the new geometry, this will demonstrate that the fifth postulate is entirely independent of the others.

In that case, the new system of views would constitute a geometry describing some conceivable world different from the Euclidean one — a world in which, through a point lying outside a given straight line, many straight lines can be drawn that do not intersect the given line.

Lobachevsky continued to clarify the course of his thought and turned to the consequences flowing from Euclid's postulates.

> "In the new geometry only two propositions are possible," the speaker continued, paying no attention to the evident bewilderment ripening among his listeners. "Either the sum of the three angles in every rectilinear triangle is equal to two right angles — and this assumption constitutes ordinary geometry; or in every rectilinear triangle this sum is less than two right angles, and this latter assumption serves as the foundation of a special geometry, to which I have given the name 'imaginary geometry'. "

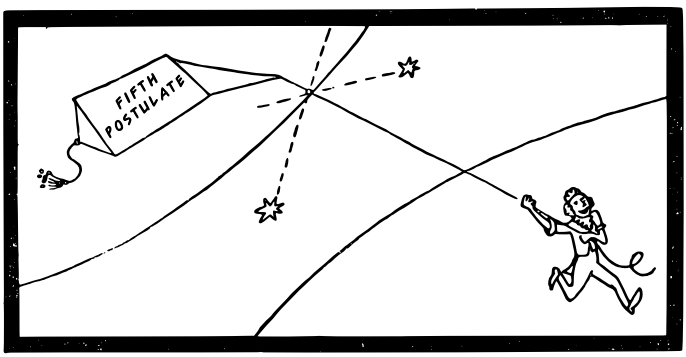
His colleagues whispered, smiled, and failed to understand why Professor Nikolai Lobachevsky needed such nonsense, why he wished to overthrow the established order of common sense. Youth, youth... He was intelligent and energetic. In time he would settle down and abandon these foolish

ideas.

They did not even attempt to understand him. Or perhaps they could not. Was this not the familiar tragedy of genius — a man advancing ahead of his age?

Especially absurd to the mathematicians sounded Lobachevsky's conclusion that in this "imaginary geometry" the angle of a triangle depended upon the length of its sides. That simply did not fit within accepted reasoning. Any side of a triangle is a segment, and a segment can be measured — in inches, arshins, miles, metres, or kilometres, if one prefers the measures introduced by revolutionary France. But what is an angle? An abstract magnitude measured in degrees or radians.

What possible relation could exist between quantities so unlike in nature?



In 1826 the ideas of Nikolai Lobachevsky found neither

sympathy nor understanding among his contemporaries. They were not visual. Had he drawn the notorious triangle whose angles summed to less than 180 degrees; had he placed into their hands a piece of surface on which the first four postulates of Euclid held true and the fifth was replaced by his own; had they been able to trace with a pencil, upon a plane of negative curvature, a line that was truly the shortest distance between two points — then perhaps they would have believed. Perhaps.

One need only recall the first telescopic discoveries of Galileo Galilei to imagine the struggle every new idea must endure before gaining recognition. Yet conservatism is not merely a negative trait of society. It acts rather like an antibiotic, protecting society from immature or fleeting notions. Truly great ideas, however, make their way regardless.

A year after his report to the department, Lobachevsky was elected rector of Kazan University. For nineteen years thereafter — re-elected four times — he stood at the helm of the university. The students, especially the mathematicians, adored their rector. Beneath his outward sternness they discerned an unmistakably large and generous heart. Numerous anecdotes about the rector circulated among the students.

On one occasion, in a bookshop, Nikolai Ivanovich noticed a young assistant absorbed in reading. The book seemed familiar. He approached. Indeed, in the young man's hands was a mathematical treatise. Lobachevsky had

to overcome many difficulties before the capable youth — I. Boltsani was his name — was admitted to the university. The rector had not been mistaken. The young man completed his studies with distinction and became professor of physics at Kazan University. And the case of Boltsani was far from unique. The rector helped many of his students, asking neither reward nor gratitude in return.

In 1829 the principal results of Nikolai Lobachevsky were published in the *Kazan Herald*. The publication brought Nikolai Ivanovich little satisfaction. Now he was openly mocked, not only by colleagues at Kazan University. The Saint Petersburg Academy of Sciences, through its respected member, Academician Mikhail Ostrogradsky, issued a negative assessment of his work. It was said that the venerable academician remarked of the Kazan professor:

> "Lobachevsky is not a bad mathematician, but when required to show an ear, he will certainly show it from behind rather than from the front."

Lobachevsky did not yield. He wrote articles in German and in French, popularising the ideas of non-Euclidean geometry. Like a solitary giant he advanced towards a goal visible to him alone. He moved forward with visor lowered, so that the arrows shot at him by "Lilliputians", as one of his pupils expressed it, might not strike him.

Yet the arrows did wound. A genius is still a man — of the same flesh and blood. What is to be done if his vision is sharper than that of others, if his intellect is stronger?

The society in which Lobachevsky lived forced those who refused to conform to pay dearly. Nor did his contem-

poraries understand the gifted Hungarian mathematician Janos Bolyai, who some years later arrived independently at views similar to those of Lobachevsky. Some sociologists today regard such resistance as an expression of society's instinct of self-preservation. Genius is always protest. One cannot take a new step without disturbing the conventional foundations accumulated by society.

Lobachevsky's "imaginary geometry" was a challenge to common sense. The bristling philistine accepted the challenge. In the reactionary journal *Son of the Fatherland*, edited by the ill-remembered Faddey Bulgarin, there appeared a mocking anonymous review. Lobachevsky's "imaginary geometry" irritated not only mathematicians.

Let us recall the spirit of the age. Not only were the postulates of Euclid regarded as sacred and inviolable truths; in philosophy the dominant influence was that of Immanuel Kant, who had moved away from the materialism of his youth. Kant maintained that space and time are not objectively real, that they do not exist among "things in themselves". In his view, space and time are merely forms of sensible intuition — structures that order the sensations received from the real world.

Thus, since space and time do not belong to an objective world existing independently of man, but are creations of the human mind, the laws of geometry need not be derived from experience. They may instead arise from our own representations. And these representations of space, so it was believed, are fixed in the unshakable postulates of

Euclid. From such reasoning the philosopher concluded that the laws of geometry are necessary and absolute, as are space and time themselves.

Lobachevsky, however, remained throughout his life on materialist ground. He held that only experience can serve as the criterion of truth for any geometry. "Ask nature," he declared in his rectorial address on the most important matters of education. "She preserves all truths and will answer your questions unfailingly and satisfactorily."

But did Nikolai Lobachevsky himself suppose that his "imaginary geometry" was not merely logically consistent, but might in fact describe the space of the surrounding world more accurately? Yes — emphatically yes. He was convinced that human beings cannot impose the laws of geometry upon nature. For that reason he rejected Kant's views.

Like Carl Friedrich Gauss, Lobachevsky attempted in practice to measure the sum of the angles of a triangle. He understood that the truth of his geometry for real space could be established only through measurements across immense distances. Accordingly, he constructed a triangle with vertices at the Earth, the Sun, and Sirius, and, using the astronomical data on stellar parallax available in his time, attempted to calculate the sum of its angles.

Alas, the precision of angular instruments in his time was insufficient, and the values of stellar parallax were only approximate. The calculated deviation of the sum of the angles from 180° lay within the limits of observational

error. Yet this negative result did not discourage the great geometer. He understood that the failure was due to the imperfection of instruments and to the fact that the chosen triangle was still too small.

A year before his death, the blind Nikolai Lobachevsky dictated in French his final work, *Pangeometry*. Euclidean geometry was not refuted by his "imaginary geometry"; rather, it appeared as its simplest special — or, if one prefers, limiting — case, when the Gaussian curvature (which is negative in Lobachevsky's hyperbolic geometry) becomes equal to zero.

The history of the gradual expansion of geometry — from the fifth postulate of Euclid to the geometries of Lobachevsky and Janos Bolyai, and further to Bernhard Riemann and Albert Einstein — stands as a serious warning to those who, in dealing with cosmology, too readily extrapolate what is known "here" and "now" to what exists and occurs "there" and "then".

It is hardly prudent, having studied the geometry of one's own room, to extend its conclusions to the universe as a whole.

6.6 The Real Construction of the "Imaginary World"

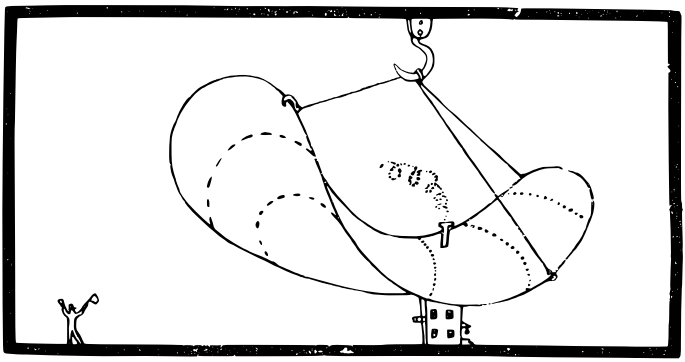
And yet Nikolai Lobachevsky was not satisfied with the results of his work to the end of his life. He was troubled by the sense of its incompleteness, by the absence of a proof that his "imaginary geometry" could not in principle lead to absurdity. He himself did not doubt its correctness — but others did. If only he could have drawn his imagined lines and figures and written upon the diagram a single word: "Look!" In ancient times that word, placed upon a figure, had replaced a proof. Alas, such an "absolute proof" he never found.

In 1868, only twelve years after the death of the great Russian geometer, the Italian mathematician Eugenio Beltrami published a modest memoir entitled *Essay on an Interpretation of Non-Euclidean Geometry*. The memoir exploded like a bomb, scattering all sceptics who had refused to believe in Lobachevsky's "imaginary geometry". It was the very work that had been lacking during Lobachevsky's lifetime.

Professor Beltrami had for some time been engaged in cartography, studying methods of representing the curved surface of the Earth upon a flat sheet of paper. In doing so he encountered the little-explored question of surfaces of constant negative curvature — a kind of sphere turned inside out, or *pseudosphere*. Long before, at the end of the seventeenth century, the "imaginary sphere" had been

discussed by Johann Heinrich Lambert — mathematician, physicist, astronomer, and philosopher. It is unlikely, however, that Beltrami was familiar with Lambert's work.

Examining a broad class of surfaces of constant negative curvature, Beltrami succeeded in constructing them explicitly. A curious reader may recognise one such surface in the form resembling a saddle. Most remarkable of all was this: the geometry on such surfaces proved to be precisely the geometry of Lobachevsky.



Then came the revelation for all who had doubted. At last Eugenio Beltrami could utter the long-desired "Look!" and point to a diagram. The pseudosphere — a surface embedded within ordinary Euclidean space — proved to be precisely the much-disputed "imaginary" plane of Nikolai Lobachevsky. If such a plane (that is, a two-dimensional space) exists, then its geometry cannot be false.

Beltrami's memoir brought about a genuine revolution. Lobachevsky's name was illuminated with the radiance of glory — though, sadly, only after his death.

It is impossible, however, to draw or vividly imagine a three-dimensional space obeying the axioms of Lobachevsky's geometry. Even analogy fails here. In the absence of visual models, one must rely upon logic.

A two-dimensional space of zero curvature is the plane. The same zero curvature characterises Euclidean space, which differs from the plane only by possessing one additional dimension.

A two-dimensional space of negative curvature is the Lobachevskian plane. The same negative curvature defines Lobachevsky's non-Euclidean space, which differs from that plane only by the presence of an additional dimension.

To picture such a space is difficult; yet mathematically it is described with complete precision. The curvature of space may be determined experimentally. In a space of negative curvature, the sum of the angles of a triangle depends upon the lengths of its sides and is less than 180 degrees. Through a point lying outside a given "straight line" one may draw not merely one but an entire bundle of "straight lines" that do not intersect the given one, and so forth.

Exactly as Lobachevsky foretold in 1826 at the meeting of the Physical and Mathematical Section of Kazan University.

Beltrami's memoir revived interest in non-Euclidean geometry. Numerous works followed. Certain peculiarities were discovered in the pseudosphere which the Lobachevskian plane itself does not possess. Mathematicians proposed other models and further interpretations, not only of the plane but also of the space of Nikolai Lobachevsky. One of these, anticipating the course of time, shall now be described.

Let us imagine a train rushing along the rails. A passenger walks through the carriage towards the dining car, in the direction of motion. What is his speed relative to the small stations flashing past the windows? The answer appears simple: it is the sum of the train's speed and his own motion along the carriage.

On his return the situation is less straightforward. Swaying slightly, he moves at various angles to the direction of the train's motion. Now his speed relative to the same stations is determined not by simple subtraction. It is not enough merely to deduct his two kilometres per hour from the train's 120 kilometres per hour. The total speed must be found as a vector difference. And the addition or subtraction of vectors follows the rule of the parallelogram.

We recall Pythagoras and are led to the thought that the laws governing the composition of velocities obey the rules of Euclidean geometry. Or, as specialists say, the geometry of velocity space is Euclidean.

Yet such a statement is pure assumption. Only experiment can decide what geometry governs velocity space.

And it was experiment that first revealed a contradiction between velocity space and the properties of Euclidean geometry. The matter unfolded in the following way.

In 1877 the American physicists Albert A. Michelson and Edward W. Morley carried out an experiment intended to clarify the contradictory properties attributed to the luminiferous ether.[25] There is no need here to enter into the technical details of the experiment or the precise aims of the investigators. What matters for us is that they compared the speed of sunlight in two directions: from east to west — along the motion of the Earth in its orbit — and from north to south, across that motion.

[25] The luminiferous ether was a hypothetical medium once thought necessary for the propagation of light waves, assumed to fill all space. Experiments such as that of Albert A. Michelson and Edward W. Morley failed to detect it, leading to its eventual abandonment in modern physics. – DM

The sum of two vectors pointing in the same direction is always greater than the sum of the same vectors inclined at an angle to one another. For this reason Michelson and Morley expected that the speed of light, combined with the velocity of the Earth in different directions, would yield different results.

Their astonishment was great when it turned out that, whatever it was combined with, *the speed of light remained the same*!

Thus the Euclidean rules for the addition of velocities proved inadequate. The geometry of velocity space, therefore, is *not* Euclidean.

Anticipating developments somewhat, we may note that in 1908 the German mathematician Felix Klein showed that the geometry of velocities coincides precisely with the geometry of Nikolai Lobachevsky.

> "Of all non-Euclidean geometries," wrote Yakov Smorodinsky, "the geometry of Lobachevsky has proved to be the most real, while the 'real' Euclidean geometry has turned out to be merely an approximate model."

6.7 The Astonishing Spaces of Bernhard Riemann

Let us continue the history of constructing new worlds, begun by our great compatriot.

In the autumn of 1853 an unknown Doctor of Philosophy, Riemann, submitted to the Faculty of Mathematics at the University of Göttingen a competitive dissertation in application for the post of "Privatdozent". According to the established rules, the candidate was required to propose three additional topics for a trial lecture. The head of the faculty approved one of them, and after the lecture the council made a final decision concerning the candidate's fitness for teaching.

At Göttingen the Faculty of Mathematics was headed by Carl Friedrich Gauss. He already knew Riemann from his doctoral dissertation. There is an opinion that he was wary of the young man's genius, seeing in him an equal.

Riemann submitted three topics for consideration. Two of them raised no doubts whatsoever. The third, devoted to the foundations of geometry, was an absolute dark horse.

Riemann himself had no intention of choosing it as the subject of his lecture. Ordinarily the head of the faculty approved the first topic on the list, and the matter ended there. Gauss chose the third.

The well-known German mathematician Heinrich Weber wrote:

> "Gauss deliberately selected precisely this topic from the three proposed by Riemann. He himself admitted that he ardently wished to hear how so young a man would find his way out of so difficult a situation."

Riemann required almost half a year to complete the work on the questions merely indicated by the title. At last the "Colossus of Göttingen" appointed the meeting of the faculty...

Riemann's lecture bore the title *On the Hypotheses Which Lie at the Foundations of Geometry*. The speaker treated geometry in its most general form, as the study of continuous manifolds — not only of the familiar three dimensions, but of any number *n* of dimensions. If, in such a manifold, the distance between infinitely close elements is defined — that is, if a metric is given — then Riemann called such manifolds spaces and characterised their properties by means of curvature.[26]

Here it is appropriate to glance briefly into the past. Reflections upon the possible existence of space with not three but four dimensions appeared in mathematics long ago. Historians trace them back as far as Diophantus in the

[26] A manifold is a mathematical space that may be curved or higher-dimensional, but which locally resembles ordinary Euclidean space. A metric defines how distances are measured within the manifold, and enables one to study its geometric properties, such as curvature, in a generalised setting. – DM

third century. In a clearer form the idea was expressed by Abu al-Wafa al-Buzjani, a native of Khorasan who worked in the tenth century at the court of the Buyids in Baghdad.

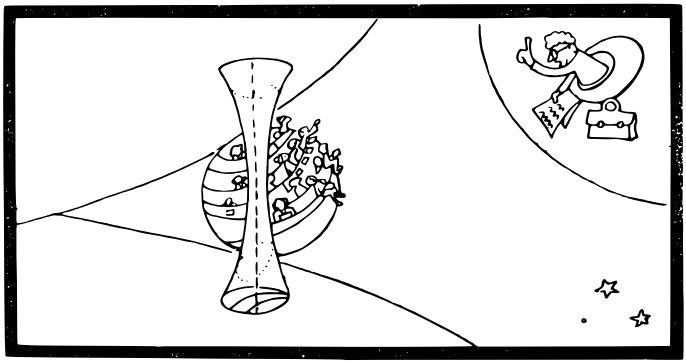
From time to time the notion of extending spatial measurement from three to four or more dimensions arose among European mathematicians, usually provoking scepticism. Matters changed in 1788, when the French mathematician Jean le Rond d'Alembert added to the spatial coordinates *x*, *y*, and *z* a fourth coordinate — time *t*. This new coordinate, however, did not enjoy equal rights with the others. In space one may move in any direction; along the road of time there is traffic in one direction only — from past to present and into the future — not the reverse, lest the principle of causality upon which the world rests be violated.

Nevertheless, after d'Alembert the idea of a fourth dimension developed further in the works of many mathematicians. Soon attention turned not only to four-dimensional space, but to five-, six-, and, in general, to *n*-dimensional spaces.

A careful reader may ask: "Who needs such fantastic constructions of abstract mathematics, impossible to picture directly?" The point is that the relations established in multi-dimensional geometry need not be interpreted as spatial in the ordinary sense. They may describe entirely different kinds of relations between objects governed by laws that require many dimensions.

One example is given by Ernst Kolman in his book *The*

Fourth Dimension.



Imagine, for instance, a cloud of gas consisting of n molecules. At any given moment each molecule occupies a certain position in space, determined by three coordinates. Yet each molecule also possesses momentum — the product of its mass and its instantaneous velocity. Momentum, too, has three components, projections upon the coordinate axes.

Thus, to specify the state of a single material point — a molecule — six quantities are required. In other words, the motion of each molecule may be described as the motion of a point in six-dimensional space called the *phase space*. The evolution of the entire system of n molecules may then be represented as the motion of a single point in a $6n$-dimensional phase space.

The trajectory of this motion, known as the *phase tra-*

jectory, describes the change of state of the whole system of gas molecules. The method of multi-dimensional phase space is employed in various sciences — in mechanics and thermodynamics, in physical chemistry and in quantum mechanics.

In his lecture Bernhard Riemann presented the principles of multi-dimensional geometry in their most general form. He took as the foundation of his investigations the Gaussian element of length — that is, the infinitesimal distance between two points. This idea had once enabled Carl Friedrich Gauss to construct the intrinsic geometry of a curved surface. There Gauss had stopped.

Riemann carried the method further. He transferred it from surfaces — from two-dimensional spaces — to spaces of three and more dimensions, generalising the idea and constructing new and remarkable geometries of remarkable worlds.

"I set myself the task of constructing the concept of a multiply extended magnitude," Riemann declared, sketching before his listeners the strange outlines of "hyperspaces". He argued that if different kinds of surfaces may exist — that is, two-dimensional spaces: flat, elliptic, or such as the Lobachevskian plane, characterised by Gaussian curvature differing in sign and magnitude — then three-dimensional and, in general, *n*-dimensional magnitudes may also exist.

In the light of these generalisations, the geometry of Euclid, the geometry of constant negative curvature developed by Nikolai Lobachevsky, and the geometry of spaces

of constant positive curvature — which we now call *Riemannian geometry* — all appear as particular cases.

Considering space of positive curvature, Riemann extended to it the properties of the spherical surface. Just as on a sphere "straight" lines cannot be prolonged indefinitely, since they close upon themselves, so in spherical space a "straight" line must likewise be closed.

One may offer the following illustration. If our space possessed positive curvature, then a ray of light or a spacecraft sent from the Earth along a "straight" path would, after sufficiently many years, inevitably return to its point of departure. And were that curvature as great as in certain works of fantasy, a person might always see the back of his own head before him.

Thus spherical space would be finite and yet without boundary, just as the surface of any sphere is finite and without edge. Accustomed as we are to the infinity of Euclidean space, such a construction is difficult even to imagine.

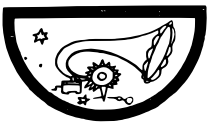
Carl Friedrich Gauss was deeply impressed by the depth of Bernhard Riemann's thought. The candidate was appointed, and three years later became a professor.

He was thirty-one years old — the son of a poor rural pastor from Breselenz — when he first gained the opportunity to devote himself entirely to science.

The content of his trial lecture was not published. Riemann did not seek publication, least of all of a work which,

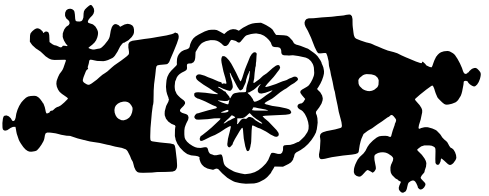
as he himself understood, was accessible only to a very limited circle. Having set forth his ideas in general form, he did not return to them. Instead he worked intensely, writing several brilliant mathematical memoirs. The Berlin and Bavarian Academies of Sciences elected him to membership. Recognition followed from the Paris Academy and from the Royal Society of London.

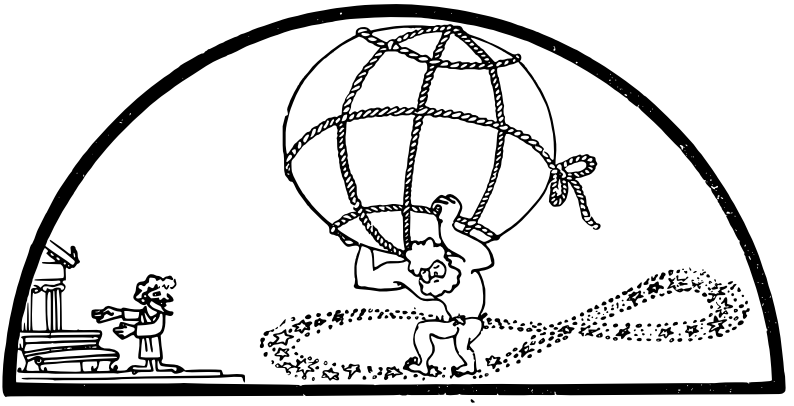
Yet at the height of his fame, in his thirty-ninth year, the "professional" disease of impoverished scholars and intellectuals of the nineteenth century — tuberculosis — struck him. By then he possessed the means to travel, and he went to Italy. But a year beneath the blue southern sky could change nothing. At the age of forty, the second great German mathematician after Gauss passed away.



Part III.

Ideas





7. The Symphony of Space-Time

Containing an account of the great discoveries of the twentieth century, and also presenting a new version of a well-known poem by Alexander Pope.

The twentieth century began turbulently. Along the roads and through the streets of cities rolled rattling automobiles, belching suffocating smoke and frightening

horses. In the sky the engines of the first aeroplanes crackled and sputtered. Electricity established itself as the principal driving force of technical progress. It was also an age of wonders for science.

In 1900 the professor of the University of Berlin, Max Planck, advanced a remarkable hypothesis: energy could no longer be regarded as continuous, but was emitted in separate portions — quanta. Thus quantum theory was born.

In the same year the Russian astronomer Aristarkh Belopolsky demonstrated under laboratory conditions the validity of the Doppler effect for determining the motion of light sources. From that moment astrophysicists were able to measure the velocities of stars with considerable reliability.

In 1901 the young German physicist Wilhelm Kaufmann showed, by means of a delicate experiment, that the mass of the recently discovered electron changes when it moves at extremely high speed. This was wholly perplexing. Mass — that venerable and, according to classical theory, constant quantity — appeared to depend upon velocity.

In 1902 Albert A. Michelson, together with Edward W. Morley, repeated the measurement of the speed of light and obtained the value 299, 890 $\pm$ 60 kilometres per second. The measured quantity did not vary under any conditions.

A year later, in Russia, there appeared the work of Kon-

stantin Tsiolkovsky, *The Exploration of Cosmic Space by Means of Reaction Devices*. In it he substantiated the possibility of using reaction engines for space travel and developed the theory of rocket motion.

Motion, motion! The twentieth century seemed to be taking revenge for the unhurried nineteenth. The striving for change seized every sphere of life and every stratum of society. Waves of strikes rose throughout the world. Alarmed by the gathering storm, the government of Tsarist Russia hastily entered into war with Japan. "A small victorious war — what could be better to calm the people?" The method was tried and old. Yet perhaps too old for a new century. The Russian proletariat answered with revolution. In 1905 a vast "general rehearsal of October" swept across the country.

In the same year an article appeared in the German journal *Annalen der Physik*, entitled *On the Electrodynamics of Moving Bodies* and signed by Albert Einstein.

To understand the significance of this event for science, however, we must first step back a little — to gain a proper run-up.

7.1 Can a "Decisive Experiment" Fail?

The restless spirit of the coming century began to reveal itself even within the outwardly tranquil nineteenth, disturbing and unsettling its contemporaries. The greatest

surprise was the Albert A. Michelson–Edward W. Morley experiment, devised to investigate whether the speed of light depends upon the motion of the medium through which it propagates.

Its results had so profound an influence upon subsequent developments that it may be of interest to recall something about the men whose names are recorded in the annals of history.

Albert Abraham Michelson was born on 19 December 1852 in the small Polish town of Strzelno near Poznan, close to the Polish–German border — so close that at the time of his birth the town belonged to Germany, having passed to it in 1772 through the efforts of Frederick the Great along with the entire Duchy of Poznan.

Life under the rule of the German Kaisers was evidently difficult, for Michelson's father, Samuel, soon emigrated to America, taking with him his modest savings, his wife Rosalia, and his two-year-old son. There is little need to describe the hardships of immigrant life. Its outcome speaks plainly enough: Samuel Michelson remained until his death the proprietor of a small haberdashery shop, barely able to support his family.

His son Albert, however, through persistence and determination, entered the United States Naval Academy. He graduated in due course, served the required period in the North American fleet, and later became a lecturer in physics and chemistry at the same academy. There he read the newly published treatise *Electricity and Magnetism* by

James Clerk Maxwell and, like physicists throughout the world, was struck by the fact that the speed of light had emerged as one of the fundamental physical constants.

It was then that the young lecturer conceived the idea of measuring that speed with the utmost possible precision. The problem became the work of his life.

Later, already an experienced experimentalist, Albert A. Michelson moved to Cleveland, to the Case School of Applied Science, where he became acquainted with Professor of chemistry and natural history at the neighbouring university, Edward W. Morley.

Those who knew them remarked how difficult it was to imagine two more dissimilar men. First, Morley was some fifteen years older — a considerable difference, given that in 1885 Michelson was only thirty-three.

Secondly, Morley descended from English settlers who had arrived in the New World as early as the beginning of the seventeenth century. Among old American families there was a traditional pride in their wandering forebears and, at times, a certain condescension towards more recent immigrants. Religious devotion was likewise characteristic of many such families. The son of a Congregational minister, Edward Morley had himself completed a theological seminary. Only an unexpectedly awakened passion for chemistry saved him from the clerical robe. He remained a deeply religious man. Indeed, he accepted his professorship on the condition that he be permitted regularly to preach sermons and to play the organ in the chapel.

Yet these differences did not prevent a close friendship between him and the convinced atheist Michelson.

Outwardly the contrast was no less striking. Having graduated from a military academy, Michelson retained throughout his life a fondness for discipline and bearing. He was slender, elegant in dress, fond of sport, and notably handsome.

Morley was the very image of the absent-minded nineteenth-century professor. Enormous red whiskers, long hair falling to his shoulders, always in motion, always possessed by ideas. An unbuttoned waistcoat or chalk upon his trousers — what trifles! He not only failed to care about his appearance; he scarcely seemed aware that such a thing existed.

Yet in their work — in the construction of apparatus and in research — these two so different men revealed an astonishing pedantry and stubbornness. Neither liked to retreat once a problem had been undertaken. Both were also passionate musicians. If Morley delighted in sitting at the organ, drawing from its pipes not only psalm tunes, then Michelson from childhood played the violin with considerable skill.

By 1885 both professors were already well known in scientific circles: Edward W. Morley for his scrupulous determinations of the proportion of oxygen in air and of the relative weights of oxygen and hydrogen in water; Albert A. Michelson for his experiments on measuring the speed of light.

In Europe, debate over the ether had been raging for several years. It was therefore no surprise that two English physicists — William Thomson and John William Strutt — both ennobled for their scientific achievements as Lord Kelvin and Lord Rayleigh respectively, invited Michelson to investigate how the medium might influence the speed of light.

The proposal was flattering. Michelson shared the idea with Morley, who at once grew enthusiastic and generously placed at his colleague's disposal the basement in which his laboratory was situated.

Their first joint work soon brought Michelson his doctoral degree.

Thereafter the friends began preparing a second experiment. It was conceived as a truly decisive test.

"Michelson and I have begun a new experiment," Edward W. Morley wrote to his clergyman father on 17 April 1887, "which ought to show whether the speed of propagation of light is the same in all directions. I do not doubt that we shall obtain a final answer."

Both investigators were convinced that by measuring the velocity of a light beam along the direction of the Earth's motion and against it they would detect a difference, prove the existence of the elusive ether — the supposed carrier of light waves — and determine the absolute motion of the Earth through that ether-filled space.

Alas, in July 1887, when the experiments were com-

pleted and the results reduced and analysed, Albert A. Michelson and Morley found that no difference whatsoever could be detected. In whatever direction the observer moved, the stubborn speed of light remained the same.

The conclusion seemed absurd. It contradicted everyday experience, which teaches that a bird flying with a tailwind moves faster than against it. Michelson and Morley prepared a brief report describing the negative result and sent it to a scientific journal. It was published that same year in England, and the world learned of the American experiment.

Much later the English physicist, philosopher, and public figure John Desmond Bernal would call it "the greatest of all negative results in the history of science." Yet in 1887 Michelson was far from convinced that the failed experiment had buried the ether once and for all. "The problem still awaits its solution," he declared publicly in lectures devoted to the work.

It is time, however, to explain why this unsuccessful experiment so profoundly stirred the scientific world — and why, having mentioned the famous paper of Albert Einstein at the close of our introduction to this chapter, we abruptly turned aside to a seemingly doubtful experiment. The moment has come to make the connection clear.

7.2 Overture to the Symphony of Relativity

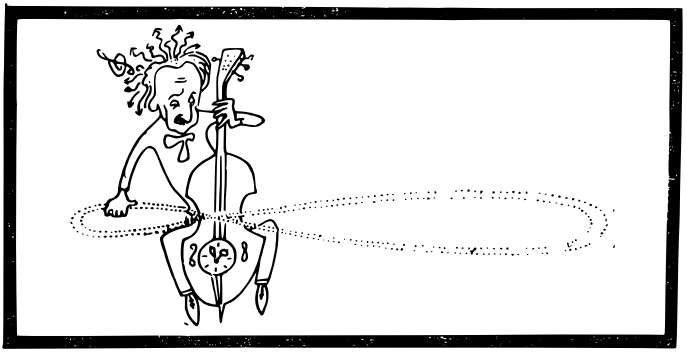
The difficulty lay in the fact that the result of the Michelson–Morley experiment could not be explained within the framework of classical theory. At that time space was regarded as something like a vast container filled with ether. The ether was considered indispensable. In it, light waves were supposed to propagate. Can one imagine waves without a medium? Such an image would resemble the smile of the vanishing cat in Lewis Carroll's *Alice's Adventures in Wonderland*: the cat disappears, leaving behind only its grin. Waves without a medium seemed equally inconceivable. Water waves are visible; sound waves travel through air; light waves were thought to travel through the luminiferous ether[27]. But what was this ether?

There was another reason for the physicists' attachment to it. Ether filled all space. Matter moved within that space. If ether were taken as a stationary frame of reference, one might speak of absolute motion, absolute space — in short, of an absolute framework for Newton's universe. The concept of ether, like Atlas, upheld the entire structure of classical mechanics.

Yet the American experiment suggested that no such ether wind existed — no current blowing into the faces of passengers aboard the Earth as it sailed through the stationary cosmic medium. The speed of light appeared independent of the observer's motion. Classical thought

[27] From Latin *lumen* (light) + *ferre* (to bear or carry) , literally meaning "light-bearing" or "light-carrying". – DM

reached an impasse. Was the measurement at fault?



At the turn of 1892–1893, Hendrik Lorentz, the creator of electron theory and a leading authority of his time, proposed what seemed a most unlikely explanation of the negative result. "We shall indeed obtain no effect," he argued, "if we assume that all bodies contract in the direction of motion."

In that case, the apparatus of the American investigators would itself become slightly shorter owing to the Earth's motion, and each light beam would traverse a correspondingly reduced distance. Lorentz even calculated the contraction. For the Earth's diameter the formula yielded a shortening of about six centimetres. He attributed this contraction to electromagnetic effects associated with the electric charges present in every atom.

To preserve the ether, Lorentz appeared to sacrifice

common sense — so it seemed on the eve of the twentieth century.

The most striking feature was that the predictions of this seemingly absurd theory agreed with the observed facts. Even so, many physicists were deeply uneasy at the freedom with which the Dutch professor from Haarlem handled common sense. They recalled the remark of Josiah Willard Gibbs: "A mathematician may say anything he pleases, but a physicist must preserve at least a little common sense."

The uneasiness increased when a letter reached Haarlem from Dublin. The Irish physicist, Professor of Trinity College, George Francis FitzGerald, informed Hendrik Lorentz that he had long been using the same hypothesis in his lectures. Unfortunately, FitzGerald disliked writing, and Lorentz later remarked that he had encountered mention of the contraction hypothesis only in a paper by Oliver Lodge.

Gradually the "wild" FitzGerald–Lorentz hypothesis began to penetrate even the fortified strongholds of orthodox physics. It alone offered a more or less acceptable explanation of the "absurd" experimental result while preserving the familiar laws of classical theory. Moreover, both authors spoke only of speeds below that of light. In the ordinary, visible world the contraction would be vanishingly small. Even for a speeding bullet — what could be swifter to the imagination? — the shortening would amount to only a billionth of a per cent. What instrument could possibly

detect so slight a change?

Yet the difficulties did not end there. In 1901 the young German physicist Wilhelm Kaufmann demonstrated that the mass of the recently discovered, rapidly moving electron was not constant. Its variation depended upon velocity and followed precisely the hypothetical FitzGerald–Lorentz law. Another pillar of the classical structure — the constancy of mass — gave way.

In 1904, at the congress in St. Louis, the renowned French mathematician and member of the Paris Academy of Sciences, Henri Poincaré, declared his conviction that no velocities greater than that of light could exist in nature. On that occasion he also formulated, for the first time in strict and general terms, the principle of relativity. No experiment performed within a laboratory, he argued, can reveal to the investigator whether his laboratory moves uniformly in a straight line or is at rest. None whatsoever.

However, having made so bold an assumption, which in effect denied the ether, Henri Poincaré hastened to add a reservation: more precise measurements might still overturn the results of the Michelson–Morley experiment.

"Now," he continued in his paper *On the Dynamics of the Electron*, published a year later, "it is in any case interesting to examine what consequences may be drawn from it." In this phrase one sees the whole of Poincaré the mathematician, for whom the knowledge of physical reality was not a matter of first importance. Indeed, as a convinced adherent of the doctrine that the essence

of things is unknowable, and denying any necessary link between essence and appearance, Poincaré held that the value of a theory lay not in how correctly it reflected reality, but in how convenient and expedient it was in use. His philosophical views were analysed in depth and criticised by Vladimir Lenin in *Materialism and Empirio-criticism*.

As a mathematician, however, the French academician was brilliant. It is enough to note that in the seven years following his graduation from the Polytechnic School in Paris he wrote one hundred and two scientific papers and notes. He was an honorary doctor of eight universities and a member of twenty-two academies.

"He anticipated the mathematical constructions of Einstein," writes the well-known Soviet historian of science Boris Kuznetsov. In effect, on the foundation of the ideas of George Francis FitzGerald and Hendrik Lorentz, Poincaré erected the first storeys of the special theory of relativity. At the time, few reflected upon this.

First, as Dmitri Ivanenko observes, Poincaré himself was not entirely confident in his results. An unstable philosophical foundation and strong ties to the classical tradition made this step especially difficult for him. Secondly, he published his work in an Italian mathematical journal that was virtually unknown to physicists. By contrast, the similar paper by Albert Einstein, which followed soon after, appeared in the widely read journal *Annalen der Physik* and was taken up by a large body of German theoretical physicists.

Not at once, however. It should be said that during the first five years after the publication of the paper, responses to it were both rare and largely unfavourable. Among the first to speak out was the already familiar Walter Kaufmann. "I foresee," he wrote, commenting on the conclusions of the special theory of relativity, "that the overall result of the measurements will be incompatible with the fundamental assumptions of Lorentz and Einstein."

Even more sceptical was the description offered by Professor of Physics at Moscow University, Alexander Timiryazev (son of Kliment Timiryazev). In the sumptuous multi-volume collection *History of Our Time* one may read:

> "It is highly characteristic that among English physicists, who embody all their ideas in concrete images and always strive to construct a clear and universally comprehensible 'model', the principle of relativity has met with almost no success."

And further:

> "But perhaps this new theory has pointed to new paths? Has it enabled the prediction of new facts not foreseen by other theories? To this one must reply in the negative, for its entire meaning consists only in bringing already known facts into a system. And if this theory — or rather its equations, which constitute its content — is destined to endure, then it is certain that they must be interpreted differently; this theory must undoubtedly assume another form — a form physically conceivable, a form that does not deny the ether — this, in the words of the celebrated Lord Kelvin, the only body known to physicists! ...It

> is curious to note that all the adherents of this new revolutionary theory are at present occupied with other, more pressing questions — and this only seven years after its birth."

Well said, indeed — especially if one considers that seven years later it was not the theory that changed to suit a "physically conceivable form", but rather the form that changed in accordance with the special theory of relativity. The ether, meanwhile, was consigned to the scrap-heap, where such notions as phlogiston, caloric, and the "horror of a vacuum" were already at rest.[28] All these had been provisional models — first approximations that had outlived their usefulness.

Yet Alexander Timiryazev continued to reject the new theory despite its successes. And he was not alone.

Albert Einstein became a symbol of the restless twentieth century. Numerous excellent books and pamphlets, articles, essays, and narratives have been devoted to a popular exposition of his ideas. The reader has no doubt encountered them. Here, however, we shall need only certain conclusions of the theory of relativity — conclusions that gave rise to a new and unusual conception, first of the structure, and then of the development, of the world in which we live.

[28] Phlogiston and caloric were earlier scientific hypotheses: phlogiston was thought to be a substance released during combustion, while caloric was a fluid believed to account for heat. Both were later abandoned as chemistry and thermodynamics developed, much like the older notion of a "horror of a vacuum," which denied the possibility of empty space. – DM

7.3 In Search of the Harmony of the Universe

When Albert Einstein was still little Albert, his father's brother — Uncle Jakob — brought him a book on algebra.

"Algebra is a cheerful science," he would say, holding the boy on his lap. "When we cannot find the beast we are hunting, we temporarily call it *X* and continue the chase until we catch it and put it in the bag."

And twelve-year-old Albert eagerly tracked the cunning *X* through the thickets of mathematical jungles. Later he became acquainted with geometry. The harmony, rigour, and beauty of Euclid's logic captivated him. How important it is to be able to perceive the beauty of a mathematical proof! For this one need not be Einstein, nor search personally for the most expressive solution. Often it is enough that someone reveals its beauty. In this, perhaps, lies one of the principal tasks of a true teacher.

A poor medical student who dined with the Einstein family on Fridays advised Albert to read popular scientific books. This literature awakened in him an interest in how the world is constructed.

Particularly strong influence on the formation of the young man's outlook was exerted by the book *Force and Matter* by the German physician and philosopher Ludwig Buchner. The materialism and atheistic character of this work appeared extraordinarily bold and innovative during

the years of rapid development of the natural sciences in Germany. The book was reprinted many times, despite its simplified treatment of philosophical questions.

The vulgar and superficial materialism of Büchner's book was criticised by Friedrich Engels and Vladimir Lenin. Yet his views helped Einstein to eradicate religious belief within himself once and for all and to become an atheist. Having lost faith in religious dogma, Einstein devoted his life to the search for a harmony of the universe capable of replacing myth with truth.

In his later years, Albert Einstein recalled that at the age of sixteen he first began to reflect on the speed of propagation of light for two observers moving relative to one another. By that time Albert was already sufficiently interested in physics to know of the much-discussed results of the Michelson–Morley experiment. He himself testified to this as follows:

> "There is no doubt," Einstein wrote in a letter to Bernard Jaffe, the author of an excellent biography of Michelson, "that the Michelson experiment exerted a considerable influence upon my work, since it strengthened my confidence in the correctness of the principle of the special theory of relativity. On the other hand, I was almost completely convinced of the correctness of this principle even before I became acquainted with the experiment and its result."

Classical mechanics rested, among other things, upon two fundamental propositions. The first was the mechanical

law of addition of velocities. We have already cited the example of a passenger walking along the carriage of a speeding train. To vary the theme somewhat, let us imagine ourselves on the deck of a steamer during a storm. The waves run in one direction and with equal speed. At the captain's command the ship turns its stern to the wind and follows the waves. After some time the speed of the ship matches that of the waves, and the scene of the storm around us becomes frozen. Our vessel, like the "Flying Dutchman"[29], stands motionless upon the crest of a wave and finds itself, as it were, in a world of stationary watery ridges and hollows.

[29] The "Flying Dutchman" is a legendary ghost ship in European maritime folklore, said to be doomed to sail the seas forever without making port. It is often used as a metaphor for eerie stillness or suspension amid a restless, moving ocean. – DM

The second proposition is the principle of relativity. Einstein himself explained it in the following way:

> "Let us imagine two physicists, each of whom has a laboratory equipped with every conceivable physical apparatus. The laboratory of one physicist is situated in an open field, and the laboratory of the other in a railway carriage rapidly moving in a certain direction. The principle of relativity asserts: if the carriage moves uniformly and without jolting, the two physicists, applying all their instruments to investigate all the laws existing in nature — one in the stationary laboratory, the other in the carriage — will find that these laws are the same. Stated in a more abstract form, this means: according to the principle of relativity, the laws of nature do not depend upon the uniform translational motion of the reference system."

It should be noted that before Einstein the formulation of

the principle of relativity referred not to all possible laws of nature, but only to the laws of mechanics.

Repeating to himself the principles of classical mechanics, Albert Einstein returned in thought to the results of the Michelson–Morley experiment. The American physicist had failed to detect any addition of the speed of light to the speed of the Earth. Why?

Einstein tried to imagine himself moving after a beam of light at a speed of 300 thousand kilometres per second. Then, according to the laws of classical mechanics, he ought to see light in the form of an electromagnetic field at rest in space, varying with time. Yet it proved impossible to picture such a situation; it simply had no right to exist.

> "Intuitively it seemed clear to me from the very beginning that, from the point of view of such an observer, everything must occur according to the same laws as for an observer at rest relative to the Earth," he later said, recalling the paradox that had occupied his mind in his youth. "Indeed, how could the first observer know or determine that he was in a state of rapid uniform motion?"

We, the contemporaries of the twentieth century, have grown accustomed to the unexpected conclusions of theory. It has even become difficult, unfortunately, to astonish us by the discovery of paradoxical phenomena or by proofs of what only yesterday seemed fantastical. This is a dubious privilege of our age. The nineteenth century knew neither such an abundance of sensational discoveries nor such a mass of science-fiction novels that, under the guise

of glorifying science, deprive readers of their capacity for wonder.

Einstein graduated from the ETH Zurich and, after a fairly prolonged search, secured permanent employment in Bern, occupying the modest post of Technical Expert, Third Class, at the Patent Office. The happiest and most productive period of his life began. Biographers often compare those years with the period of Isaac Newton's life in Woolsthorpe Manor during the London plague.

> "Drawing up patent specifications was a blessing for me," Einstein wrote in his autobiography a month before his death. "It compelled me to think much about physics and provided occasion for it. Moreover, a practical profession is, in general, a salvation for people like myself: an academic career forces a young man continually to produce scientific output, and only strong characters can resist the temptation of superficial analysis under such pressure."

In Bern, Albert Einstein became closely associated with several young men who, like himself, were interested in physics and mathematics. An unusually close-knit circle was formed, which its members called the "Olympia Academy." The young men walked together, read philosophical works that were difficult to tackle alone, argued at length, and exchanged ideas. Einstein, a man of very modest needs in everyday life, was happy. "Just think," he wrote to one of his friends who had left Bern, "apart from eight hours of work, there remain eight hours of daily idleness and, in addition, Sunday."

The result of such an intense intellectual life, combined with complete indifference to material advancement, was that in 1905 Einstein wrote several scientific papers and sent them to the journal *Annalen der Physik*. One of them, as he wrote in a letter to a friend, "...proceeds from the concepts of the electrodynamics of moving bodies and modifies the doctrine of space and time...". This was the special theory of relativity.

In it, by extending the classical principle of relativity — advanced by Galileo Galilei only in relation to mechanical processes — to optical and all other phenomena, and by replacing the mechanical law of addition of velocities with the postulate that the speed of light is independent of the motion of its source, Einstein constructed a new mechanics. His theory was free from the contradictions encountered by classical theory in explaining the experiments of Michelson-Morley and Walter Kaufmann.

The perceptive reader may already have noticed a repetition of the story of the discovery of non-Euclidean geometry.

By rejecting the unconditional and universal validity of Euclid's postulate on parallels and replacing it with what at first glance seemed the absurd assertion of the opposite character, Nikolai Lobachevsky arrived at the discovery of a new geometry.

In the same way, the "absurd" postulate of the constancy of the speed of light led Albert Einstein to the creation of a new mechanics, distinct from the classical mechanics of

Isaac Newton. The analogy may be continued. Just as the geometry of Nikolai Lobachevsky differs but little, for small distances, from the geometry of Euclid, so Einstein's mechanics yields results that are practically indistinguishable from classical results when dealing with velocities much smaller than the speed of light.

The author has already mentioned that many excellent books on the theory of relativity have been written by Soviet and foreign specialists. One of them is surely to be found on your own shelf, dear reader. For that reason, the author will not strive to invent new examples and analogies. Moreover, in our time the theory of relativity has ceased to be something extraordinary. Young people first encounter its paradoxes in adventure novels, then study it at school and in the early years of university. It is true that some make use of the fashionable name merely to wave a hand and pronounce the well-worn phrase: "Everything in life is relative."

By somewhat broadening the understanding of the semantic nuances of the expression "theory of relativity," the author wishes to remind the reader that this term does not imply the relativity of human knowledge, but only the relative equivalence of reference frames (or coordinate systems) moving at constant velocity with respect to one another. Nothing more...

7.4 The Fourth Dimension

Professor of mathematics Hermann Minkowski, whose lectures the student Albert Einstein had once so diligently skipped, said with astonishment to Professor of Physics Max Born after reading the paper in *Annalen der Physik*:

> "It came as a great surprise to me. My Zurich student Einstein? Why, formerly he was a real idler and did not concern himself with mathematics at all..."

At the Polytechnic, Einstein enrolled in thirteen mathematical courses at once, six of which were delivered by Minkowski. Yet he attended lectures rarely, preferring to study independently the questions that interested him. Compulsory study of subjects was unbearable to him.

> "It is in fact almost a miracle," he wrote towards the end of his life, "that modern methods of instruction have not yet entirely strangled the holy curiosity of inquiry; for this delicate plant requires, besides encouragement, above all freedom — without it, it inevitably perishes."

Here, one may suppose, Einstein somewhat overstated the case.

However, this unflattering opinion of the student Einstein did not prevent Minkowski from becoming so deeply impressed by the ideas of the special theory of relativity that he undertook the development of its mathematical apparatus.

Hermann Minkowski (1864–1909) lived a short life, outwardly not rich in events. He was born in Russia, in the

small town of Aleksoty in the Minsk province. Later, like Albert A. Michelson, he was taken by his parents away from his native land — though not across the ocean, but to Germany. There he completed his secondary schooling and university education, and there he distinguished himself through works devoted to the geometric theory of numbers. He is now rightly regarded as the founder of that branch of mathematics, although geometric methods in number theory had been employed by other mathematicians before him.

Toward the end of his short life, Minkowski turned to the geometrisation of another theory — this time a physical one, today known as the special theory of relativity.

In 1908, at a congress of natural scientists and physicians in Cologne, Hermann Minkowski delivered his famous lecture on the geometric foundations of the theory of relativity, entitled *Space and Time*.

> "No one has ever observed a place except at a particular moment in time," said Minkowski, "nor any time except at some particular place." He called a point in space corresponding to a given moment in time a "world point," and the totality of all conceivable world points, for brevity, the "world." To any body existing for some time in space there would then correspond a certain curve—a world line.
>
> "The whole world," Minkowski continued, "appears resolved into such world lines... and the physical laws might find their most perfect expression as relations between these world lines."

Thus arose the four-dimensional world of space–time, created in order to solve problems concerning phenomena occurring at sub-light speeds by means of the new theory of relativity.

Let us once more recall the essence of the four-dimensional nature of this world, so as to be convinced that there is nothing miraculous about it.

What, then, distinguishes the familiar three-dimensional world from the four-dimensional space–time of Hermann Minkowski? Above all, the latter is by no means a marvel. It is not some fanciful invention of an eccentric mathematician, but the entirely real world in which we live, dear reader. One need only look at our surroundings from a slightly different point of view. Let us consider an example...

The author hopes that the reader will not object to the assertion that any event always occurs at some point in space and at some moment in time. Even the most distinguished detectives of our age require answers to the questions *where?* and *when?* in order to reconstruct the dynamic picture of an incident.

The first question, "Where?", is easily answered if one knows one's own coordinates, say (x_1, y_1, z_1), and the coordinates of the place of the event, (x_2, y_2, z_2). One then estimates the distance by solving the well-known equation

$$r^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2.$$

In this way one obtains the complete spatial description

of the event in the Newtonian sense.

To give the picture a dynamic character, one must answer the second question, "When?". For this purpose, the approximate moment of the event and the moment when information about it was received are denoted respectively by (t_2) and (t_1). One then forms the equation for the time interval:

$$t = t_2 - t_1.$$

Only when equipped with the above equations can one begin the investigation.

However, how much more swiftly would the inquiry proceed if Monsieur Hercule Poirot and Commissaire Maigret knew and employed the geometric foundations of the theory of relativity.

In the four-dimensional world of space–time, instead of two separate equalities, a single space–time interval between events is introduced:

$$S^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2 - c^2(t_1 - t_2)^2.$$

Here c is the speed of light, approximately (300,000) kilometres per second. The product $c^2(t_1 - t_2)^2$ has the same physical dimension as the remaining terms of the equation, and thus, from a formal standpoint, everything is in order.

The essential point, however, is that the written equation does not change when passing from one reference system moving uniformly and rectilinearly to another system moving no less uniformly and rectilinearly, though in

a different direction and with a different velocity. Such an equation is said to be *invariant*, and the systems are called *inertial*.

The author now invites the reader to notice the similarity between the two equations: that of the familiar three-dimensional world and that of the four-dimensional space–time world. The difference lies in only one term, bearing a minus sign. And it is precisely here that a subtle trap awaits us.

Depending on the magnitude of $c^2(t_1 - t_2)^2$, the square of the interval S^2 may be greater than zero, equal to zero, or even less than zero. This means that, unlike the ordinary Euclidean space of Newtonian mechanics, Minkowski's "world" is divided into regions separated by surfaces that may be constructed by setting

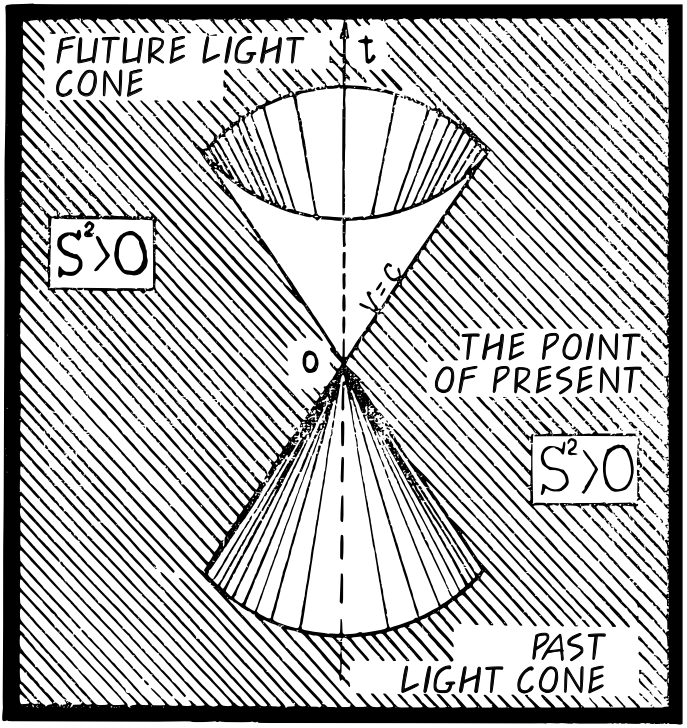
$$S^2 = 0.$$

Such surfaces are called *light cones*.

Now, if the reader is willing to sacrifice one spatial dimension, one may attempt to depict the world with two remaining spatial coordinates and one temporal coordinate. In the figure one sees what specialists call a three-dimensional space–time continuum.

Inside the cones, where $S^2 < 0$, we encounter the world of normally causally connected events. The interval between the original world point O and any other point lying within the given light cone is such that signals have suf-

ficient time to travel from one point to the other with a speed not exceeding the speed of light.



It is interesting to note that the lower cone, relative to the point *O*, represents the region of the absolute past. The upper cone represents the absolute future. The reader has likely already realised that the central point *O* is associated with any given initial event.

The past light cone includes all directions along which information carried by light from celestial objects reaches the observer. The observer is always located at the point in space and the moment in time through which the vertex of the light cone passes.

One of Einstein's collaborators in Princeton, later Professor of Physics at Syracuse University, P. Bergmann, gives in his book *The Riddle of Gravitation* a particularly illuminating example explaining this model:

> "...any direction on the light cone of the past may be associated with a point on the celestial sphere, which represents the picture revealed to us when we observe the sky and the stars (just as a globe reflects our conception of the Earth). The angle between two visible positions of stars — the measurement of such angles is very important for astronomers — is the angle between two light directions on the past light cone.
>
> If two observers move relative to one another with velocities comparable to the speed of light, the angles they determine between directions to the same stars will not coincide. This must be so, because the relative positions of the stars depend essentially on the motion of the Earth, defined within a particular inertial frame of reference. However, over half a year the Earth's velocity changes by two ten-thousandths, (2×10^{-4}), of the speed of light due to its annual motion around the Sun. This gives rise to an apparent displacement of the stars. This phenomenon is known as the aberration of light."

A completely different situation arises in the region outside the cones. A causal connection with an event lying outside the light cone is, in principle, impossible, since it would require a velocity exceeding that of light.

Of course, the depicted picture of the light cones never remains motionless. The central point (O), in which you, dear reader, are seated — even if you are perfectly at rest in your own frame of reference — is your "world point". It continually creeps along the time axis, carrying the light cones with it, like a snail carrying its shell.

By introducing the concept of a four-dimensional world of events, Hermann Minkowski made a substantial contribution to the development of relativity, as well as to modern space–time concepts in physics.

> "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics. Therein lies their strength. Their tendency is radical. Henceforth space by itself and time by itself are destined to fade into mere shadows, and only a kind of union of the two will preserve an independent reality."

So he spoke in Cologne in 1908 before the Society of German Natural Scientists and Physicians.

Let us now attempt a preliminary and modest conclusion. Newton's theory described events satisfactorily by assuming space to exist absolutely, independently of time and of the matter contained within it. Time, too, depended on nothing — a single universal time flowing uniformly

throughout the infinite world.

Soon, however, discrepancies and paradoxes began to accumulate — phenomena that classical Newtonian theory could not explain. Then, through the efforts of George FitzGerald, Hendrik Lorentz, and Henri Poincaré, new ideas were advanced which formed the basis of the special theory of relativity later developed by Albert Einstein.

This theory shattered the old conception of the universe. Yet it did not discard Newton's theory. Whenever events occur at speeds negligible compared with the speed of light, the "good old equations of Sir Isaac" continue to serve faithfully. The new conclusions merely generalised them for velocities approaching that of light.

Einstein's relative world was certainly far less comfortable and familiar than Newton's. It lacked definiteness and mathematical finality; and, if one dared to use the word, it lacked "absoluteness" — though now in a new sense, no longer the Newtonian one.

And at this point it becomes necessary to mention the work of Hermann Minkowski.

Minkowski wrote: "Neither Einstein nor Lorentz touched the concept of space..." Of Hendrik Lorentz he said that Lorentz believed in the existence of an absolutely stationary ether and absolute time. Of Albert Einstein he remarked that Einstein "rejected time as a concept 'unambiguously determined by events'."

The revision of the notions of space and time Minkowski

claimed for himself. In his constructions, instead of the absolute Newtonian space and absolute Newtonian time discarded by the new theory, he introduced his own absolute world of space–time. This world described reality at a new level — more complex, yet closer to nature, closer to truth.

7.5 George FitzGerald — Hendrik Lorentz — Henri Poincaré — Albert Einstein — Hermann Minkowski — Special Theory of Relativity

The ideas of the special theory of relativity were, as it were, in the air. They had been prepared by the entire development of the "well-established" physics of the nineteenth century. The theory matured within classical physics itself, and this is why it produced such an unprecedented resonance in the world. Never before had a scientific theory affected such broad circles of society so deeply.

Humanity truly split into two camps. One consisted of those who discerned in the new theory the coming progress and the inevitable transformation of world-views. The other included those who could not accept the new conclusions. The Secretary of the French Academy of Sciences, Emile Picard, even much later, in 1922, confessed: "The theory of relativity is for me like a red rag to a bull!"

Yet for the development of science it was important that the problem left no one indifferent.

Many scientists worked on the creation of the special theory of relativity. Who, then, is its true author? To whom should the palm of priority be awarded?

Einstein remained a very modest man throughout his life. In 1955, shortly before his death, he wrote:

> "Recalling the history of the development of the special theory of relativity, we may say with certainty that by 1905 its discovery had been prepared. Lorentz already knew that the transformation which later received his name was of essential importance for the analysis of Maxwell's equations, and Poincaré developed this idea..."

In his own work he regarded as new only the fact that it showed "that the Lorentz transformations go beyond Maxwell's equations and concern the very essence of space and time."

In this final remark lies the essence of Einstein's role.

If George FitzGerald had only ideas, and Hendrik Lorentz constructed a theory concerned solely with electrical phenomena — and moreover "never claimed authorship of the principle of relativity", remaining within the framework of non-relativistic classical physics — then the case of Henri Poincaré is more complex.

The French mathematician approached the very boundary of the new conception: "Perhaps we must construct an entirely new mechanics, still vague as yet, in which inertia

increases with velocity and the speed of light is the limiting speed." "This," as the philosopher Gerald Holton writes, "illustrates the strength of his intuition and the qualitative character of his insight."

> "Why," asks Louis de Broglie, "did Poincaré fail to step beyond the limits of his own thinking?" — and he answers: "Undoubtedly this occurred in part because he was a pure mathematician.
>
> He adopted a rather sceptical position with regard to physical theories, believing that in general there exists an infinite number of different yet logically equivalent points of view and representations, which the scientist chooses merely on grounds of convenience."

Einstein's work absorbed the thoughts and ideas that were in the air. He generalised the achievements of his time and made a leap into the unknown by constructing a theory of space and time.

It is fair to regard as creators of the new picture of the world those whose names appear in the title of this section as well. In 1909 Max Planck wrote:

> "Hardly needs it be said that the new, Einsteinian approach to the concept of time demands from the physicist the greatest capacity for abstraction and an enormous power of imagination. In its boldness this theory surpasses everything that had previously been achieved in the speculative investigation of nature and even in the philosophical theory of knowledge; ... the principle of relativity has every right to claim real physical significance. In its depth and

> consequences, the revolution brought about by the principle of relativity in the sphere of physical views can be compared only with the revolution produced by the introduction of the new picture of the universe created by Nicolaus Copernicus."

However, Albert Einstein himself spoke of this work far more reservedly:

> "I do not at all understand why I am exalted as the creator of the theory of relativity. Had I not existed, within a year Poincaré would have done it, within two years Minkowski would have done it; in the end more than half of it belongs to Lorentz. My merits here are exaggerated..."

And after a pause, with a sigh, he would add:

> "As for the theory of gravitation, I am almost certain that if it had not been I, no one would have discovered it even to this day..."

He spoke these words later, after he had achieved recognition, after he had become, during his lifetime, a great figure, when if not all, then many of the difficulties of constructing the general theory of relativity — sometimes called "Einstein's theory of gravitation" — were already behind him. And there had been many of them...

7.6 The next step was inevitable...

The Special theory of relativity did not fully satisfy Albert Einstein in his search for harmony in the structure of the

universe, nor in his desire for a sufficiently complete and convincing explanation of its workings. Its conclusions applied only to systems moving uniformly and in straight lines. But what of systems undergoing acceleration?

Any acceleration, however slight, destroyed the uniformity of physical processes. The geometric properties of real space–time proved to be far more complex than those of Hermann Minkowski's "world". They could change with time, depend upon physical processes, and manifest themselves in experience as gravitation.

The next step in the investigation therefore became unavoidable. Einstein had to determine what effects an observer would detect if space itself were not described by Euclidean geometry. This meant entering a new domain — the theory of gravitation. Yet to take this step required ten years of intense labour. The result was a set of equations describing the gravitational field, together with explanations occupying four pages of the paper published on 2 December 1915: *The Foundation of the General Theory of Relativity*.

For the remainder of his life, with only minor exceptions — such as the 1924 paper generalising the idea of the Indian physicist Satyendra Nath Bose — Einstein devoted himself to developing the principles he had discovered in 1915.

The middle of the second decade of the twentieth century was a difficult time. The third year of the First World War was drawing to a close. Crutches struck against the pavements. Blind soldiers, their eyes burned by poisonous

gas and hidden behind blue spectacles, stood silently in long queues for rations. Bread was rationed; coal was rationed. In Imperial Germany tobacco was not issued at all.

In Berlin, in Haberlandstrasse, on the seventh floor of number five, in a cold and unheated room, Professor Einstein worked with an unlit pipe between his teeth. He was writing his paper on the general theory of relativity. It introduced even more radical changes in humanity's conception of space and time than the special theory had done.

The principal aim he set himself was to reconcile Isaac Newton's doctrine of gravitation — according to which gravitational force acts instantaneously — with the conclusions of special relativity, which assert the constancy of the speed of light and the principle of relativity.

Whether that reconciliation is conceptually complete is a deeper question — and one that still invites scrutiny.

The most important fact placed at the foundation of the General theory of relativity was the equality of the gravitational mass of any body (that is, the mass which creates its gravitational field) and its inertial mass — the resistance the body offers, while in a state of uniform rectilinear motion, to any change in that state under the action of an external force.[30]

On the basis of this fact, Albert Einstein formulated the principle of equivalence, according to which it is impos-

[30] The equivalence of gravitational and inertial mass means that the mass determining a body's gravitational interaction is equal to the mass measuring its resistance to acceleration. This equality, well supported by experiment and elevated by Einstein to a postulate (the

sible to distinguish gravitational force from inertial force. Motion in a gravitational field is always equivalent to free motion by inertia. In short, in Einstein's theory there is no gravitational force in the Newtonian sense. All familiar processes — the fall of a stone to the Earth, the motion of planets around the Sun, or of satellites around planets — occur by virtue of inertia.

At first sight this sounds like an absurd paradox. From school we are taught that free motion is uniform and rectilinear. Yet satellites and planets move along ellipses. A stone in a gravitational field falls with acceleration. Where, then, can free motion take place? Evidently only in space completely cleared of gravitating masses — in empty space.

Indeed, the farther we move away from the Sun, the weaker its influence becomes, the larger the radii of planetary orbits, and the more their motion appears to straighten. Similarly, the higher we rise above the Earth, the smaller the acceleration of a freely falling body.

The apparent contradiction disappears if one takes into account that, according to general relativity, motion by inertia occurs in curved space–time.

The properties of physical space in the vicinity of gravitating masses differ from those of space far from them. As Yakov Borisovich Zeldovich and Igor Dmitriyevich Novikov wrote in their article *General Relativity and Astrophysics*, the structure of the General theory of relativity is such that the equations of the gravitational field are compatible only with motions of matter that satisfy the laws of conservation

of energy and momentum.

This means that, whereas in classical theory the field equations existed separately from the equations of motion, in general relativity the gravitational field equations themselves contain the equations of motion. In principle, this important issue was resolved by Albert Einstein together with his collaborators Leopold Infeld and Banesh Hoffmann. Soviet theorists Vladimir Alexandrovich Fock and Nina Ivanovna Petrova obtained similar results for ordinary matter.

In developing general relativity, Einstein also created a distinctive mathematical apparatus for it, known — in keeping with our fondness for analogy — as pseudo-Riemannian geometry.

If we imagine that you and I are drifting uniformly through "empty" four-dimensional space–time, the lines of our lives would be represented by certain straight lines — recalling Hermann Minkowski's world-line. But the moment we encounter a mass possessing gravitation, our world-lines would bend.

Thus, if one were to undertake a distant space voyage and attempt to record the world-line of one's flight, one might expect that, in passing near planets, the line would bend slightly (since their gravitational fields are comparatively weak); near stars, the curvature would be considerably greater; and in the intergalactic expanses the world-line would almost straighten again, for there the gravitational fields are exceedingly faint.

"Interesting! Could one then, by abandoning the very notion of gravitational force, replace its action by the curvature of world-lines? Or, since the totality of world-lines constitutes the 'world', by the curvature of space–time itself?.."

Yes — that is precisely the conceptual shift introduced by the General theory of relativity. What had previously been called a force becomes a manifestation of geometry.

It was not easy, however, even for many outstanding scientists brought up in the traditions of visual classical physics, to understand and picture the physical ideas of general relativity. The mathematical apparatus of the theory was extraordinarily complex. And the corrections to Newtonian gravitation, obtained through laborious calculation, turned out to be so minute that they could extinguish all enthusiasm. These circumstances greatly hindered the new theory from gaining popularity among scientific minds.

Even Max Planck, who had enthusiastically welcomed the creation of special relativity, once remarked to Albert Einstein with a certain sadness about general relativity:

"Everything was explained so well — why did you begin dealing with these problems again?..."

Apparently it was then that an additional couplet appeared to the famous poem by Alexander Pope mentioned at the beginning of the book. To avoid repetition, the author presents it in a slightly altered version, though the meaning remains the same:

> The planetary world lay wrapped in darkest night,
> As if in veils concealed from human sight. God said,
> "Let Newton be!" — and all was light.

The added lines fall out of the solemn ode-like style and resemble more the rapid speech of modern times:

> But Satan would not long accept defeat;
> Then Einstein came — and darkness was complete.

Nevertheless, even this entirely "mad" theory — from the standpoint of common sense — found supporters, though they were few.

Once, after a lecture on the foundations of the General theory of relativity delivered by Arthur Eddington at the University of Cambridge, a colleague approached him to shake his hand and express his gratitude.

"An excellent lecture, Professor Eddington. You are truly one of the three people in the world who genuinely understand the meaning of the theory of relativity."

Noticing a slight embarrassment on Eddington's face, he continued warmly:

"I assure you, it is really so — you need not be embarrassed..."

"No," Eddington replied, "I am merely wondering who you consider to be the third."

Too much in the history of the radical transformation of our ideas about the universe is connected with Eddington's name to pass him over in silence.

Arthur Stanley Eddington was born on 28 December 1882 into a family with long-standing farming traditions. From an early age he displayed a phenomenal memory and an interest in large numbers. By modern standards he was a typical prodigy. As a child he set himself the task of counting all the letters in the Bible. It is not known how successful he was in this enterprise. Yet on clear evenings he would always try to count the stars in the sky. This childhood passion later allowed him to say: "I began attacking large numbers in astronomy when I was six years old."

Before entering school, young Arthur could not read, yet he already knew the multiplication table from beginning to end. After finishing school with the highest recommendations, he entered Trinity College, Cambridge, where the names of Isaac Newton, Lord Rayleigh, James Clerk Maxwell and J. J. Thomson were known simply as those of former students.

During these years, Arthur Eddington was an exceptionally sociable and witty student, brilliantly mastering one course after another. Everything seemed to come easily to him. At the mathematical society of Trinity College, Cambridge he successfully presented a paper entitled *The Velocity of Gravitation.* He joined the chess club and soon became its president. He took to cycling excursions and entered another society known as the "$\Delta^2 V$ Club," where within nine months he rose from an ordinary member to secretary and then president. Later he would belong to many more clubs. The collecting of clubs and voluntary societies, after all, is a distinctly English trait.

In February 1906, upon completing his studies, Eddington was appointed chief assistant at the Royal Observatory, Greenwich. By 1914 he had become director of that same observatory. In recognition of his scientific achievements he was elected to the Royal Astronomical Society, where he too soon became president.

Eddington's interests were remarkably diverse. He studied the motion of stars and the structure of stellar systems, and he produced the first theory of the internal structure of stars. Quite apart from this stands his immense work in testing, introducing, and popularising the ideas of the General theory of relativity.

In 1918, at the request of the Royal Society, Eddington prepared a *Report on the Relativistic Theory of Gravitation,* which was published as a separate volume. It was the first complete exposition of general relativity to appear in England.

In 1919, Arthur Eddington took part in the expedition organised on his initiative to test the bending of light rays during a solar eclipse. The observations confirmed the prediction of the General theory of relativity, and Eddington was awarded a government prize of £ 1,000.

A year later he published *Space, Time and Gravitation*; three years afterwards appeared his celebrated *The Mathematical Theory of Relativity*, which is still read with interest by students specialising in the subject. Later he turned to quantum theory.

Eddington's great achievements in astronomy and physics, together with his kindly and even-tempered character, earned him not only immense authority but also genuine respect. He had many pupils and continued working until the last day of his life, which came on 22 November 1944.

He was a member of several foreign academies and scientific societies. He authored thirteen books and 161 scientific papers. His final work was an article entitled *The Evolution of the Cosmic Numbers*. Captivated since childhood by the beauty of the heavens and of mathematics, Arthur Stanley Eddington remained faithful to that love until the end of his life.

The Royal Astronomical Society later established the Eddington Medal, awarded for outstanding contributions to theoretical astrophysics.

7.7 "Look!"

You will remember, reader, that once this word, placed beneath a diagram, replaced long arguments for the ancient geometers. The diagram was regarded as the highest proof of correctness. Indeed, if a figure has been constructed, why prove the possibility of constructing it?...

In our time the magical word "look!" has been replaced by the results of experiment. A theory whose conclusions are confirmed by experience is considered valid. But can

the conclusions of the general theory of relativity be confirmed experimentally?...

Albert Einstein himself pointed to three consequences that would allow the correctness of the theoretical conclusions to be tested. The first concerned a change in the frequency (or wavelength) of light when a ray propagates in a gravitational field. The second stated that the orbits of planets and satellites must continually rotate, advancing beyond the amount that can be calculated from the formulas of Isaac Newton's theory. The third effect, which could be observed within the Solar System, consisted in the deflection of a ray of starlight as it passes near a large gravitating mass, for example the Sun. It was this last consequence of the general theory of relativity that was tested before the others. Einstein proposed comparing the positions of stars in the sky when the Sun stands in the path of the ray from a chosen star. This could be done at the moment of a total solar eclipse, when stars appear in the darkened sky. The comparison had to be made with the picture of the sky when the Sun was not there.

The simplicity of the experiment is deceptive. In reality, carrying out such measurements is incredibly difficult. Even near the edge of the solar disc, the calculated deflection of a light ray amounts to an arc of less than two seconds. And since the apparent position of all stars in the sky depends rather strongly on the properties of the Earth's atmosphere, detecting these "two seconds of arc" is a task of exceptional difficulty.

By 29 May 1919, two astronomical expeditions had assembled in the zones of total solar eclipse — in Guinea and Brazil.

Arthur Eddington, who was in the first group, was very nervous — he so much wanted the experiment to succeed. Once, shortly before the journey, a colleague asked him: "What will happen if you confirm the effect?", who happened to be nearby, replied: "Then Eddington will go mad, and you will have to return home alone."

In Guinea, where the expedition had travelled, the sky was overcast from the morning of 29 May. Only shortly before the end of the total phase of the eclipse did the clouds disperse, and the necessary photographs of the starry sky were taken.

The processing of the photographs lasted several months. But in September Hendrik Lorentz informed Albert Einstein by telegram that the conclusions of the general theory of relativity had been confirmed.

After his report on the results of the expedition at a joint meeting of the Royal Society and the Royal Astronomical Society in London, the President of the Royal Society, J. J. Thomson, said: "This is not the discovery of an isolated island, but of an entire continent of new scientific ideas. It is the greatest discovery since Newton."

Since then, such measurements have been carried out many times during solar eclipses — in 1922, 1929, 1947 and 1952. Almost all of them produced similar results. Unfortu-

nately, in all these experiments the accuracy has so far been insufficient to allow completely final conclusions. The Earth's atmosphere greatly hinders astronomers. When an astronomical observatory is opened on the Moon, there can be little doubt that one of its first observations will be a test of the bending of a light ray near the Sun. For the present, scientists prefer to say cautiously that there are grounds for considering the curvature of space to be experimentally confirmed.[31]

[31] See the note on page 323.

The second effect that makes it possible to verify the correctness of the conclusions of the general theory of relativity concerns the motion of the point of Mercury's orbit nearest to the Sun. Such a point of any planet's orbit is called the perihelion. Today, however, when the number of artificial satellites of the Earth has long since exceeded a thousand, it hardly seems necessary to explain such terms.

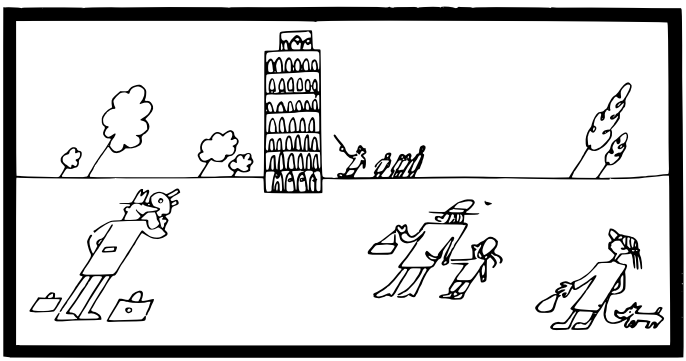
In 1859 the famous French astronomer Urbain Le Verrier, while studying the motion of the planet Mercury, discovered disturbances in its orbit that could not be explained by the action of the other planets within the framework of Newtonian theory. The perihelion of Mercury's orbit turned by thirty-one seconds of arc per century more than the theory allowed. Le Verrier tried to attribute these irregularities to Vulcan — a hypothetical planet orbiting even closer to the Sun. However, the existence of such a planet was not confirmed.

The Englishman Simon Newcomb, using his own more precise theory of the motion of the major planets, refined

the difference in the displacement of Mercury's perihelion and obtained eleven seconds more — 42″ per century. Of course, one might give a visual example of what these 42″ amount to. At arm's length, it is no more than the thickness of the page on which this text is printed. And yet these forty-two seconds weighed heavily upon the shoulders of astronomers.

Classical theory required that the perihelion of the orbit of the "messenger of the gods" should shift by 531″ per century. But observations stubbornly showed 574″. Where did they come from?... This was all the more puzzling because in every other respect the motion of the planet did not in any way contradict the laws of Isaac Newton.

And then the general theory of relativity appears. At once comes a most important result — the perihelion of Mercury, owing to relativistic effects, must shift by 43.03″ more than follows from classical theory.



Do you see?... 574″ – 531″" = 43″", and the theory of relativity gives 43.03″"! Of course, the measurements were not identical – some were more precise, others less so. It is interesting here to note the work of the Soviet astronomer G.A. Chebotaryov. He examined many old observations of Mercury's orbit and, using refined values of astronomical constants and planetary masses, found the discrepancy between observation and classical theory to be 42.65 ± 0.5. As you can see, this is in excellent agreement with the predictions of general relativity.

Naturally, it was tempting to test the value of the secular perihelion effect for other planets as well, using observational data. The figures obtained were as follows: for Venus – 8.4 ± 0.8, for the Earth – 5.0 ± 1.2, for Mars – 1.1 ± 0.3 arcseconds per century. These values also turned out to be in very good agreement with the predictions of general relativity. The theory gave for Venus 8.6″, for the Earth 3.8″, and for Mars 1.4″.

In general, today the confirmation of this effect is regarded as one of the most important proofs of the correctness of the ideas of the general theory of relativity.

The "reddening" of the light quantum (photon) has also been confirmed. This phenomenon testified to the correctness of a fundamental conclusion underlying general relativity – demonstrating the influence of gravity on the frequency of light. The researchers Robert Pound and Glen Rebka succeeded in registering the reddening of light even under laboratory conditions on Earth, under the influence

of our planet's gravitational field.

Of course, the data cited above should not be regarded as a final experimental verification of the general theory of relativity, as though nothing further remained to be done. On the contrary — experiments must continue, with their precision constantly increased by means of new technical methods.

Academician Vitaly Ginzburg also speaks of this, proposing the use of balloon-borne equipment raised into regions of highly rarefied atmosphere, as well as instruments placed on satellites, to observe the deflection of light rays passing near the Sun. This would make it possible to measure the deflection of light independently of solar eclipses.

The observed rotation of Mercury's perihelion agrees with the theoretical value within the achieved accuracy of 1%. But if one were to launch an artificial planet into an orbit with a large eccentricity, the relativistic formula could be tested with much greater precision. True, serious obstacles still stand in the way of such an experiment — both technical (placing a spacecraft into an orbit with very large eccentricity and tracking it) and theoretical. It is not yet entirely clear how to take into account light pressure, the solar wind, and the possible oblateness of the Sun.

Finally, the refinement of the orbit of the Earth's natural satellite will also help to test the conclusions of general relativity. For this purpose, the Soviet lunar rover delivered corner laser reflectors to the surface of the Moon.

There are also further possibilities for testing general relativity beyond the experiments proposed by Albert Einstein. For example, the relativistic effect in radar ranging of planets. According to the theory, in a gravitational field a light ray must not only bend but also be delayed. That is, the time required for a light signal to travel from the Earth to Venus or Mercury, passing near the Sun, must be greater than when the signal travels to the planets far from the gravitating mass of our star.

Admittedly, this delay is extremely small — no more than 2×10^{-4} s. Yet it must exist. Therefore it can and must be detected. So far this experiment has been carried out with limited accuracy — of the order of 20 %. But quite recently a group of American researchers under the leadership of John D. Anderson tested this effect in communication with an artificial celestial body launched by the American interplanetary spacecraft "Mariner". The theoretical predictions were confirmed with an accuracy of about 10 %.

An independent and extremely interesting experiment for testing general relativity would be the observation of the relativistic precession of a gyroscope's axis — that is, an additional rotation of the axis compared with the value predicted by classical theory. The equations of general relativity make it possible to calculate this correction. Three years ago such an experiment was in preparation.

Finally, a brilliant proof would be provided by the observation of gravitational waves. In Newton's classical theory

it is assumed that the action of the force of gravitation is transmitted instantaneously. Therefore no "waves of gravitation" can exist in a vacuum. It is quite different in general relativity. In the theory of the gravitational field, gravitational waves are as inevitable as the existence of electromagnetic waves. Yet this is an experiment of extraordinary difficulty.

In 1970 there appeared a report by Professor Joseph Weber claiming that he had succeeded in detecting gravitational waves. So far, however, no one has managed either to reproduce his result or to identify the source from which they came. Nevertheless, the matter is so interesting that at gravitational conferences throughout the world Weber's experiment remains constantly at the centre of attention.

Verification is necessary! But this does not mean that verification implies distrust. The results of such tests help to refine the provisions of the theory and to indicate directions for further development. One should not forget the words of the creator of general relativity himself — that every theory will eventually hear its own "no".

At present we may say that, at the existing level of development of science and technology, no contradictions have been revealed in testing the foundations and consequences of general relativity, "and in this respect there are no indications of the incorrectness or limited domain of applicability of Einstein's general relativity (we refer, of course, only to macroscopic phenomena, or more precisely, to the non-quantised domain). All consequences

that have so far been observed, as the data have been refined, agree better and better with general relativity" — thus writes Academician Vitaly Ginzburg in assessing the latest results of the verification of Albert Einstein's general theory of relativity.[32]

This theory has become a reliable foundation of modern cosmology.

In the last years of his life he turned to the new theory of gravitation and was the first to apply the conclusions of general relativity to the problem of finding the gravitational potential of the field created by a massive spherical body in the surrounding space. In other words, he solved the problem of determining the structure of a star's gravitational field in the space around it.

At sufficiently large distances from the mass, the solution yields the gravitational potential familiar to every school pupil from Newton's law. In general, if the gravitating body has a moderate mass — for example, if it is an ordinary star like the Sun — then the Schwarzschild solution does not differ greatly from the Newtonian one. But let us imagine that the star begins to contract.

A description of such a situation is given in a popular form in the book *The Riddle of Gravitation*. A much more detailed account is presented in the serious work *Relativistic Astrophysics* by Yakov Zel'dovich and Igor Novikov. For introductory purposes, however, a general view will suffice.

[32] Since the 1970s, far more precise confirmations have been obtained using radio astronomy and space-based measurements. Observations of quasars using Very Long Baseline Interferometry (VLBI) have measured the deflection of light by the Sun to an accuracy better than 0.01%. In addition, phenomena such as gravitational lensing — where entire galaxies bend light from more distant objects — provide striking large-scale confirmation. More recently, observations of gravitational waves by detectors such as LIGO, and precision timing in satellite systems, have further verified Einstein's theory to remarkable accuracy. – DM

Thus, the smaller the volume of the star becomes, the greater its density, and the more strongly the gravitational fields manifest themselves. The curvature of space-time around such a body increases. We already know that curvature may be described by means of a radius of curvature. The greater the curvature itself, the smaller the radius that measures it. If the radius of curvature only slightly exceeds the size of the body itself, the field near it may be regarded as "strong".

To picture this more clearly, let us suppose for a moment that the entire mass of the Earth were concentrated at a point. Then the radius of curvature of space–time would be approximately 1 cm. If we perform the same operation with the Sun, the curvature of space–time could be detected at a distance of about 1.5 km from the central point. This distance becomes equal to the so-called *gravitational radius*.

A sphere with a radius equal to the gravitational radius, drawn around a large mass, is called the *Schwarzschild sphere*. It is an extraordinarily interesting region of the "world".

And since the author once devoted no small effort to the field of science fiction, at the sight of so tempting an object as the Schwarzschild sphere he simply cannot deny himself the pleasure of recalling the sins of his youth.

So then — carefully now, fiction!

> “...Swallowing up space, the cosmic liner rushed forward irresistibly! The disabled engines were silent. In the dark compartment of the astronavigator (because of the need to save energy, the lighting was rarely switched on) an oppressive silence reigned.
>
> — Commander, the instruments are recording acceleration. But the engines are not working, and ahead along our course there is not a single luminous massive object whose field we could have entered... Meanwhile, our speed is approaching “*c*”.
>
> The commander sighed inaudibly...
>
> — The formulas of Isaac Newton’s theory are no use here.”

What follows is a monologue revealing the inner struggle between duty and feeling in the commander’s soul — for he, of course, has long understood everything. The author asks forgiveness for an omitted detail. The chief astronavigator of the spacecraft... But you have surely guessed... She is intelligent, wonderfully beautiful, and only twenty... no, twenty-three... In short, the commander loves her.

At the end of the inner monologue duty prevails, and the commander says evasively:

> “— We are in a trap. The field of a ‘black” star has caught us in gravitational pincers. The ship is flying closer and closer to the Schwarzschild sphere that surrounds a collapsed supergiant...”

The astronavigator at once understands the terrible truth of his words. A feeling that has suddenly flared up tells her that she must continue asking questions, in order to give

this stern and infinitely dear man the chance to speak. She asks:

> "— But if there is a star ahead — and even a supergiant — why do we not see its light?
>
> — A former supergiant," the commander corrects her bitterly. "The star's equilibrium was disturbed, and collapse set in... The outer layers fell towards the centre, drawn by a monstrous force of gravitation. The matter was compressed. The nuclei of atoms, stripped of their electron shells, are crushed, squeezed, and lie densely packed next to one another. Rays of light emitted by the collapsed body cannot escape beyond the limits of the Schwarzschild sphere and move within it along curved, closed space... Look!"
>
> He rose abruptly and went to the forward porthole. She felt his large and powerful body very close beside her — it seemed that if she stretched out her hand she would touch his beating heart. And ahead, amid the faint shimmer of phosphorescent nebulae, there gaped an impenetrably black patch — a coal sack...
>
> "Photons whose trajectories pass near — no farther than 2.6 gravitational radii from the centre of the collapse — are also captured, falling into a gravitational grave..."
>
> A cosmic chill seemed to breathe from these words.
>
> "— But they must see us, save us..."
>
> His large hand slowly rested upon her shoulders, wrapped in a soft sweater.
>
> "— For observers outside we shall approach the

Schwarzschild sphere for an infinitely long time.

— Infinitely long? Then we shall not fall into the clutches of the "gravitational grave"?..

— Infinitely long according to distant clocks. According to the clocks on board the starship, we shall cross the Schwarzschild sphere and fall onto the central body in a finite time."

For a while she remained silent.

What follows is yet another inner monologue, revealing the depth of the astronavigator's feeling and having no direct relation to the depth of the "coal sack".

"— ...But perhaps it would make sense to send out a light distress signal?

— Too late! As we approach the gravitational radius, the redshift of the light signal we emit increases sharply, and the frequency of the light, as it reaches distant receivers, will tend towards zero. Our signal will not be seen."

The ship was doomed. For a moment, forgetting herself, feeling only the warmth and weight of his hand upon her shoulders, she tried out of habit to calculate in her mind the velocity of the fall according to Newton's formula — and discovered that it had exceeded "*c*". And then, in the dark space of the navigation compartment, on the edge of the gravitational grave, their hands found one another..."

To continue this sad story, which befell simple and good people, the author has no strength. He is certain that the reader also feels the drama described very deeply. For one

would have to be heartless to see in this tale merely five unexpected consequences to which general relativity leads when bodies approach the critical gravitational radius of the Schwarzschild sphere.

The author cannot continue his account of the brave conquerors of space for another reason as well: no signal from within the Schwarzschild sphere can break through to an external observer. Nevertheless, the curious and moderately sentimental reader will surely wish to know what awaits our heroes next.

The space inside the Schwarzschild sphere also possesses two sharply distinct regions. They may be called the "inner region of the past" and the "inner region of the future". From the external world one can observe events taking place in the 'inner region of the past", and it is even possible to send signals into the "inner region of the future" — but not the other way round. No signals from the "inner region of the future" can reach the region outside the Schwarzschild sphere. And those who have fallen there will feel very alone indeed.

They would still see the external region, although they would be unable to communicate with it. Indeed, those who had "fallen in" ought to know this from theory, for it would not at all be obvious. From the point of view of the inhabitants of such an "inner world", the signals they send out in all directions would propagate quite normally. Only the "world" itself inside the sphere would appear as something like a multilayered expanding sphere, whose

outer shell would recede from the observer at the speed of light, hiding everything beyond it behind a boundary which specialists call the "event horizon". It is clear that no signals from the inner inhabitants would ever reach their colleagues and inconsolable companions who remained in the external world. For no signal can overtake the "event horizon" receding at the speed of light.

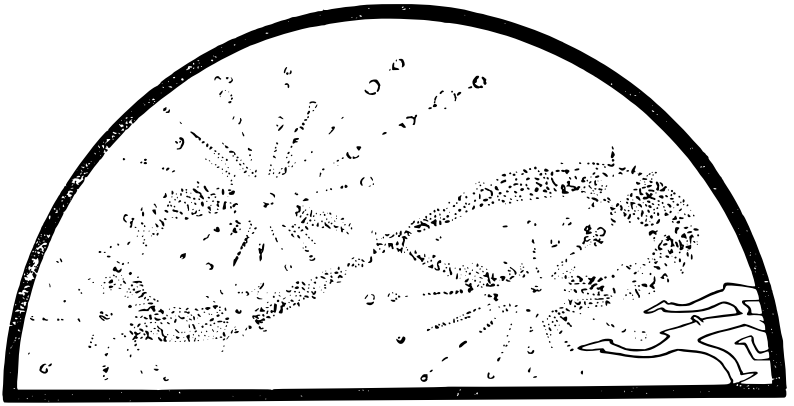
Of course, all the paradoxical consequences described above, following from general relativity, may cause a sceptically minded reader merely to shrug. "Why," he may say, "are all these puzzles needed? We live in conditions of a weak gravitational field, and such extreme curvature of space, up to the formation of an event horizon, can concern only the imagination of theorists."

Yet this is not quite so. First of all, as we penetrate deeper into the universe, who knows what we may encounter. Nature is generous in her inventions. In recent years alone she has presented us with quasars — celestial objects whose luminosity exceeds by a hundred times that of an average galaxy containing 1×10^{11} stars. What is the nature of space near such monsters of the stellar world?

The discovery of pulsars revived discussions concerning neutron stars — celestial bodies composed of heavy elementary particles and having densities of about one million tons per cubic centimeter.

Finally, the conclusions we have considered prove extremely fruitful in the discussion of cosmological models — that is, when we turn to the object of our immediate

interest. Let us therefore consider that a new instrument for understanding the universe — general relativity — has been forged and tested in a first approximation. It is time to put it to work.



8. The Priest, the Prize, and the Point of Origin

In which the reader becomes acquainted with yet another great discovery and, against his will, is drawn into a struggle between extreme and irreconcilable points of view.

We remember, dear reader, that the task of cosmology is to study the structure of the universe as a whole. The ideas that existed in the nineteenth century were based

on the classical theory of Isaac Newton. It was therefore natural that, having created a new theory of space and gravitation, Albert Einstein should turn to constructing a new model of the world as well...

8.1 Nineteen Hundred And Seventeen, February

The year Nineteen Seventeen! A year of great upheavals in the life of nations, in politics and in science. In February, in Berlin, the tenth volume of the journal *Proceedings of the Prussian Academy of Sciences* appeared, containing a short article signed by Einstein. The article was entitled *Cosmological Considerations on the General Theory of Relativity* and occupied only ten pages. Yet this was enough for the birth of modern cosmology — a science that not only possesses its own theory, but also lays claim to experimental confirmation of its conclusions.

Newton's universe, attacked by the paradoxes of Heinrich Olbers and Hugo von Seeliger, had by the beginning of our century become for physicists and astronomers a vague and indefinite concept. Its infinity in the Newtonian sense led to photometric and gravitational paradoxes, contradicting observation. Both paradoxes testified to a catastrophic difficulty within classical physics. One need only reflect that the very existence of the universe seemed to contradict it.

It was also impossible to remain with the view of William Herschel, who supposed that in empty infinite space there existed only a single stellar system with a finite and well-defined number of stars. In that case the heavenly bodies would have to attract one another and merge into a single mass.

Newton's universe, described by the laws of Euclidean space, did not correspond to observed reality. The world was different — not as the nineteenth century had imagined it. Carefully assembled "brick by brick", the edifice of the cosmos collapsed like a house of cards under the pressure of revealed contradictions. Urgent and decisive measures were required in order to restore harmony to the picture of the universe. It was necessary to find such a model of the world as would not contradict the already discovered and verified laws of physics, would withstand the paradoxes of Heinrich Olbers and Hugo von Seeliger, and at the same time would predict new results open to experimental verification on the basis of the growing technical possibilities of astronomy and physics.

The reader will presumably recall that many sought a way out of the impasse created by the gravitational and photometric paradoxes and by the second law of thermodynamics. The author has already mentioned the elegant mathematical solutions of Carl Charlier, whose hierarchical structures were free from paradoxes. The astrophysicist Robert Emden constructed so-called isothermal spheres, in thermodynamic equilibrium and resisting "heat death". In 1897 the problem of investigating a homo-

geneous stationary model was solved by L. Bianchi, who found nine different types of homogeneous spaces. All of them were spaces of constant curvature and, as S. Schüking and O. Heckman write, "possessed the property that any observer in any direction sees the same picture of the world."

Nevertheless, none of the investigators succeeded in constructing a model of the universe without a centre and at the same time free from the gravitational and photometric paradoxes, as well as from thermodynamic difficulties.

The author is now convinced that the reader clearly understands the situation in which Einstein's work appeared. First of all, it was necessary to decide which canons of the old theory could be abandoned. The Newtonian model of the universe, which had exhausted itself, rested upon three "pillars":

1. the stationarity, or invariability, of the universe in time;
2. the "cosmological principle", or "world postulate", of homogeneity and isotropy — implying the absence of a single centre of the world and the impossibility of privileged directions within it;
3. the Euclidean nature of space.

Which of these was to be sacrificed?

The way out was indicated by general relativity. It generalised Newton's theory of universal gravitation, bringing it into accordance with the principle of relativity. True, in

doing so the geometry of the world became non-Euclidean. And Albert Einstein sacrificed this "pillar".

He proposed, instead of Newton's infinite, stationary, homogeneous universe with flat Euclidean space, a finite model with a Riemannian closed three-dimensional space (a three-dimensional sphere), yet still homogeneous and stationary. However, in order to construct his model, Einstein had to modify somewhat the gravitational field equations derived in general relativity. "I have come to the conviction," he wrote, "that the gravitational field equations which I have hitherto used require a certain modification."

The reason was that the only stationary solution of the original equations led to flat Minkowski space, which in principle differed in no essential way from Newton's universe and therefore represented a trivial result.

And it was then that Albert Einstein introduced into his equations a cosmological term associated with a certain constant Λ — introducing it only after much hesitation, since this step was "not justified by our actual knowledge of gravitation". Yet there was no other way.

In the Newtonian approximation, the presence of the cosmological constant in the gravitational equations corresponds to the introduction of additional forces into the universe — forces proportional to distance. The constant Λ is very small, and therefore at short distances the influence of the cosmological term is negligible. The modified Einstein equations with the Λ-term differ very little from the original ones. Quite another matter arises when the

distances under consideration acquire cosmological scale — that is, when they become equal to tens or hundreds of millions of parsecs...

For this reason the constant Λ is called the *cosmological constant*. The forces of attraction acting between the cosmic contents of a closed universe attempt to draw matter together into a single mass. In the equation, the cosmological term with $\Lambda > 0$ would play the role of repulsive forces maintaining the universe in equilibrium. The same would occur in the opposite case. If one imagines that the matter of the universe is not contracting but, on the contrary, dispersing in different directions, then the Λ-term with $\Lambda < 0$ would play the role of an additional attraction, holding the universe in an unchanging state.

"The newly introduced universal constant Λ is determined if the mtean density of distribution (of matter in the universe) — ρ, preserved in the state of equilibrium — as well as the radius of the spherical space R and its volume $2\pi^2 R^3$ are known," wrote Einstein.

The reader should not be disturbed by this unusual form. We are dealing with a three-dimensional sphere in four-dimensional space-time. Thus the familiar surface area of a two-dimensional sphere in our ordinary three-dimensional world — $4\pi R^2$ — in four dimensions becomes a hypersurface and is calculated by the formula $2\pi^2 R^3$.

Thus there arose a static, time-invariant, closed and homogeneous model of the universe, obeying the axioms of non-Euclidean geometry and sustained by an artificially

introduced repulsive force — a force of negative pressure.

To picture Einstein's universe more clearly, let us turn to a familiar method — a thought experiment. Suppose that, having set out from the Earth, we were able to maintain our direction of flight strictly along a "straight line", for example along the path of a light ray. If the space of the universe possesses overall positive curvature, then we should inevitably return to our starting point in space. This means that, having begun our journey from a terrestrial cosmodrome and striving to move as far as possible from the initial point, we would nonetheless, after billions of years, return to it again.

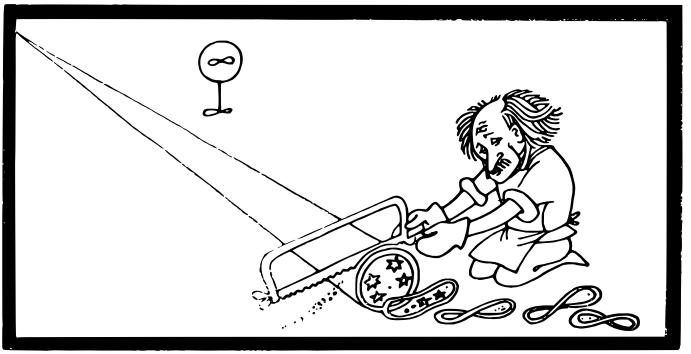
The model becomes more vivid if we compress three-dimensional space into a two-dimensional surface, while leaving the time coordinate as an unchanged straight line extending to infinity. The result is an enormously long tube — a cylinder. By this analogy, the first model of the world proposed by Albert Einstein on the basis of general relativity received the name of the "cylindrical" universe.

The author hopes that the perceptive reader has already concluded that if all the devices employed — including the introduction of the unjustified Λ — had led to only one possible solution, namely the model of a 'cylindrical" universe, this would have meant the complete defeat of general relativity — 'a modest third-class funeral". Einstein himself understood this. Yet the unusual ideas of the theory were compelling...

In that same year, 1917, the Dutch astronomer Willem

de Sitter (1872–1934) developed, on the basis of general relativity, a model in which time was curved just as space was. Now, setting out from a point in space and maintaining a straight course, a traveller would have to return not only to the same point in space but also to the same moment in time. However, in constructing his model, de Sitter assumed that there was no matter in it. His model was empty — a vacuum model, as one would say today.

Strictly speaking, this assumption contradicted one of the fundamental principles of general relativity, according to which it is precisely the presence of matter and its motion that determine the geometrical properties of the world. In the complete absence of matter (including gravitational fields), space-time should be flat.



Why, then, did de Sitter's model still possess curvature? The reason lay precisely in Λ — the cosmological term in Einstein's equations, which acted as a source of gravity,

curving space-time.

The absence of matter was, of course, a weak point of de Sitter's model. Yet it had one significant virtue. According to de Sitter's theory, the farther the gaze of an Earth-bound observer penetrated into space, the slower the processes there would appear to unfold. However, should one undertake a journey "into these distant regions of sloth and leisure" aboard a spacecraft, we would observe, as we approached, a gradual acceleration of the passage of time. By the moment of our arrival, life would be proceeding at its normal pace. This phenomenon could be interpreted as a prediction of future redshift. Unfortunately, at that time, no one paid attention to it.

Today, de Sitter's model is frequently used by theorists for approximate studies. Einstein held the Dutch astronomer's work in very high regard. "We are indebted to him for profound investigations in general relativity," he later said.

Willem de Sitter was born in the last quarter of the nineteenth century — the "age of calm and satisfaction in science". Although most of his creative life fell in our turbulent times, de Sitter remained until the end a typical scientist of the previous century.

Indeed, he accepted special relativity and even, in 1911, attempted on its basis to explain certain discrepancies in the motions of the Moon and planets.

Indeed, he absorbed the ideas of general relativity and

was the first to give it a cosmological application, and in his later years devoted much attention to the problem of the expanding universe.

But all this merely indicates his lack of conservatism. He was the "last of the Mohicans" among observational astronomers. He preferred to look through the telescope eyepiece himself, while others had already delegated this work to a photographic camera; he engaged in astrometry and passionately measured the positions of stars based on his own observations. De Sitter was an astronomer in the fullest sense of the word. It should also be added that, having been born in the Netherlands and graduated from a university there, he spent almost his entire life working in Leiden, seeking neither honours nor personal gain. Yet the work of this modest and unambitious man greatly strengthened the position of the new theory, contributing to the fame of its creator.

Einstein's renown grew especially after Eddington's expedition and the confirmation of general relativity during the solar eclipse of 1919. In the book *Einstein*, Professor B.G. Kuznetsov[33] quotes the Polish physicist Leopold Infeld, who had worked with Einstein for many years, on the reasons for the "unprecedented rise in popularity" of the author of relativity.

[33] Available here. – DM

> "This occurred after the end of the First World War. People were weary of hatred, killings, and international intrigues. Trenches, bombs, and murders left a bitter taste. Books about the war were neither bought nor read. Everyone awaited an era of peace

> and wished to forget the war. And this phenomenon could capture human imagination. From a land covered with graves, eyes turned to a sky strewn with stars. Abstract thought carried a person away from the sorrows of everyday life. The mystery of the solar eclipse and the power of the human mind, the romantic scenery: a few minutes of darkness, followed by the bending of rays — all so different from the oppressive reality... The longing for peace, it seems to me, was the main reason for the growing fame of Einstein."

But fame never comes alone. At the very moment when the progressive part of the scientific community recognised the theory, persecution of its creator began, along with attempts to undermine confidence in it. The enemies of revolutions and of progress understood the explosive force of the new theory. They also understood that the time when science could be separated from political life had passed. From then on, science became a real force in social struggle.

In Germany special organisations arose with the aim of combating the influence of Einstein's theory. Even some prominent physicists and philosophers, unable to come to terms with the new view of the world, tried by every possible means to refute its conclusions. The paradoxes of relativity found themselves at the very centre of political conflict.

> "In recent years the whole world has been in a state of mental and physical unrest," wrote bitterly one of the professors of Columbia University. 'In all like-

> lihood, the war and the Bolshevik revolution were the visible result of a deep intellectual disorder. This unrest has manifested itself in a desire to cast aside tried methods of government in favour of radical and untested experiments. The same feeling of unrest has invaded science. Many would compel us to discard established theories and instead to build the foundation of modern scientific and mechanical development upon speculative methodology and fantastic notions of the universe."

Yet neither malicious attacks nor open slander could halt the chain reaction of recognition of the theory of relativity. On the contrary, all this only drew greater public attention to it and raised still higher the popularity of conclusions that renewed old, almost instinctive conceptions of the World.

8.2 "I Only Solve The Equations"

In 1922 an article sent from the new, post-revolutionary Russia appeared in the Berlin journal *Zeitschrift für Physik*. It was entitled *On the Curvature of Space* and was signed by Alexander Friedmann. The paper was very short, and the author's name was entirely unknown in the West. Yet this Petrograd mathematician seemed to be attempting to correct Einstein himself.

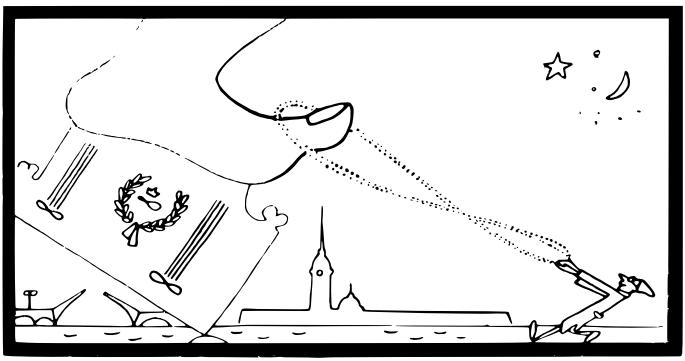
Here the author permits himself a brief digression in order to draw the kindly reader's attention to the fact that

the models of the universe proposed by Einstein and de Sitter on the basis of solutions to the gravitational equations were, as it were, polar opposites. They corresponded to two extreme points of view.

Einstein's universe was "filled" with matter, but it was static, and there was no place in it for redshift. De Sitter's universe, on the other hand, predicted the existence of redshift, yet it was empty. Evidently the truth ought to have lain somewhere in between.

In 1922, however, no one was yet thinking about redshift, and the idea of the universe as a motionless world abiding in eternal rest seemed entirely logical.

According to the solutions of Alexander Friedmann, the geometry of the universe changes continuously in time. The distances between all its parts must increase, while the curvature of space-time and the density of matter must decrease. A wholly astonishing conclusion.



In August the journal containing Friedmann's article reached Albert Einstein. Einstein read the paper. Einstein shrugged his shoulders. He did not believe in the correctness of the solutions found by Friedmann and dashed off a few lines to the journal, in which he categorically declared that Friedmann's work was probably incorrect and that the results of the Petrograd mathematician were doubtful. The editors promptly printed the reply.

Quite some time passed. The substantial German journal first had to reach Russia; then, from there to Berlin, the physicist Yuri Krutkov travelled on a visit, carrying a detailed letter from Friedmann to Einstein. As a result, in that same respected Berlin journal there appeared a new article by Einstein: *Note on the Work of A. Friedmann 'On the Curvature of Space'.*

> "In my previous note I criticised the above-mentioned paper. However, my objection was based on a computational error, as I became convinced, on the advice of Mr. Krutkov, from a letter by Mr. Friedmann. I consider Mr. Friedmann's results correct and thorough. It turns out that the field equations admit, alongside static solutions for the structure of space, also dynamic (that is, time-varying) centrally symmetric solutions."
> A. Einstein, Berlin (received 13 May 1923).

A fine and instructive example of scientific objectivity and goodwill.

The brief "conflict between Friedmann and Einstein" attracted general attention. It was a genuine scientific dis-

pute, and Friedmann prevailed. Yet, strictly speaking, there was no real dispute. The physicist Albert Einstein, proceeding from purely physical considerations, sought a stationary solution of his equations because he was convinced of the immutability of the universe.

For the mathematician Alexander Friedmann, physical conditions were not the primary concern.

> "On this matter," said Pyotr Kapitsa in his opening address at a session of the Division of Physical and Mathematical Sciences of the Academy of Sciences of the USSR dedicated to Friedmann's memory, "it is sometimes said that Friedmann did not greatly believe in his own theory and regarded it merely as a mathematical curiosity. He supposedly remarked that his task was to solve the equations, while specialists in physics should concern themselves with the physical meaning of the solutions."
>
> This ironic comment by a witty man about his own work cannot alter our high estimation of his discoveries. Even if Friedmann was not certain that the expansion of the universe, which followed from his mathematical calculations, actually exists in nature, this in no way diminishes his scientific merit."

Who, then, was Alexander Friedmann, who entered into dispute with "Einstein himself"?

Alexander Alexandrovich Friedmann was born on 17 June 1888 in St. Petersburg into an artistic family. His father was a musician and composer; his mother was the daughter of the Czech composer Vojacek.

As a boy, Friedmann was brought up by his father's relatives. For a time, during the disturbing years of the first Russian revolution, he even lived with relatives in the Tsar's residence — the Winter Palace. There remain recollections of how the eighteen-year-old Sasha Friedmann, inspired by the rising and formidable wave, wrote leaflets in the Winter Palace. His friend Volodya Smirnov — later the distinguished Soviet mathematician, academician and State Prize laureate Vladimir Smirnov — would come, collect the proclamations, and distribute them throughout the city.

In 1905, together with Tamarkin (also a future professor of mathematics), Friedmann, then in his final year at the gymnasium, wrote his first scientific paper, devoted to Bernoulli numbers. The publication appeared a year later in a respected scientific journal issued by such well-known mathematicians as Felix Klein and David Hilbert. In that same year, 1906, Alexander Friedmann graduated from the gymnasium with a gold medal and entered St Petersburg University, enrolling in the mathematical section of the Faculty of Physics and Mathematics.

In his later university years Friedmann became fascinated by dynamical meteorology — the complex mathematical theory of atmospheric motion. The mathematical apparatus of the dynamics of continuous media perfectly suited the young man's interests. It should be noted that in the field of partial differential equations, by which atmospheric processes were described, the Russian mathematical school of those years held a leading position in world science.

Differential equations are mathematical relations that connect, for example, the rate of change of a quantity with the value of the quantity itself. Accelerations, determining the rate of change of the rate, may also enter the equations. Having established the dependence between the given quantity, the rate of its change, and its acceleration, the mathematician solves the equation and obtains a formula by which the value of the required quantity can be found at any moment in time. If one reflects upon such calculations, it becomes clear that differential equations are capable of describing concrete natural phenomena in the most general and comprehensive manner.

Usually mathematicians pay little attention to the applied questions that may be clarified by a "pure" solution of differential equations. Alexander Friedmann, however, held a different view. Professor Alexander Gavrilov wrote in his memoirs:

> "A.A. Friedmann possessed rare mathematical ability. Yet the study of the mathematical world of numbers, space, and functional relations alone did not satisfy him. Even the world explored by theoretical and mathematical physics was insufficient for him. His ideal was to observe the real world and to create a mathematical apparatus that would allow the laws of physics to be formulated with proper generality and depth, and then, without further observation, to predict new laws."

Friedmann had a remarkable gift for grasping real phenomena as a whole. Understanding that any knowledge is only an approximation to truth, he developed a style of

work that has since become fundamental in theoretical research.

At the first stage, he regarded it as the theorist's task to simplify reasonably — to idealise the problem under consideration. Everything secondary must be discarded. This stage concluded with the formulation of systems of equations or inequalities expressing the problem in pure mathematical language.

Then began the second stage — solution. Here there was no physics, only mathematics. And only when the final formulas had been derived could their merit and the degree of simplification be assessed — and that solely by experiment. Only experience confirms the right of a theory to exist.

From his portrait there look at us attentive, ironic and somewhat sad eyes behind spectacles. An intellectual to the marrow of his bones, he volunteered for the army at the first shots of 1914. Alexander Friedmann was assigned to an aviation detachment as a private. For an ordinary soldier, war means the end of civilian science. But Friedmann was no ordinary soldier.

> "At present I am engaged on the question of determining temperature and pressure when the velocities are given ... " he wrote from the front. "Then I intend to write, if you find it convenient, a short note for the Geographical Collection on the causes of the origin and disappearance of vortices in the atmosphere, at least in general mathematical form — it would be very interesting."

And in another letter:

> "In the detachment, to relieve boredom, I am learning a little to fly." And somewhat further: "For reconnaissance flights I have been recommended for the St George's weapon, but whether I shall receive it is a great question. Of course, it may seem petty of me to be interested in such matters as an award, yet what can one do — such is human nature, one always wishes to 'play a little at life'. "

The breadth of Alexander Alexandrovich's interests was remarkable. He worked in theoretical meteorology and electrodynamics. During the war of 1914 he obtained the rank of pilot and turned to the theory of bomb-dropping. He wrote two fundamental works on cosmology. And in July 1925 he made, together with the pilot Pavel Fedoseenko, a record balloon flight.

A graduate of St. Petersburg University, he was among the few scholars who entered the service of the revolutionary proletariat of Petrograd and remained faithful to his people until the very end — until his untimely and accidental death from typhus in 1925.

First of all, these models were non-stationary. The radius of curvature and the density of matter in the universe changed with time. The fate of the model depended on the chosen value of the mean density.

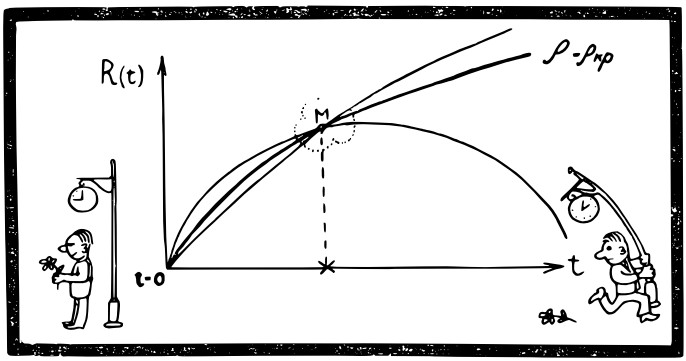
Let us suppose that $\rho = \rho_{crit}$: the mean density is equal to a certain critical value. This value can be calculated by a simple formula using several "world constants", but

that is not necessary here. It is sufficient that such a value exists. At the critical density the spatial part of the four-dimensional world is flat. However, this is not the motionless world model of Hermann Minkowski mentioned earlier. Friedmann's solution made the universe dynamic.

All distances in space increase; particles recede from one another with a speed which, for small separations, is approximately proportional to the distance itself.

For clarity, if we abandon one dimension and pass to a two-dimensional space that changes with time, such a model may be imagined as a rubber sheet being uniformly stretched in all directions. Specks of dust stuck to its surface would represent stellar systems — galaxies.

Look at the diagram. It shows a graph of how distances change in such a model. A dry abstract curve in fact conceals an entire adventure story, only written in code.



Let us begin deciphering it from the extreme left-hand point of the graph. It clearly indicates that once all distances between any two points in the universe were negligibly small. There was no space, no time, no stars, no planets, no nebulae — nothing. This is the region of zero time.

Then some mechanism began to operate. Matter appeared, its particles started to fly apart, time began to flow, and space began to expand. The distances between any two particles increased with a speed proportional to the distance itself. That means distant particles recede faster, nearby ones more slowly.

For the stretching sheet this causes no difficulty. Mark one speck of dust on its surface and imagine that it is you, the observer. As the surface expands, the nearest speck will move away from you with a certain definite speed. A more distant speck will appear much swifter. Its speed will be greater than that of the nearer one, and so on.

Later this solution was used by Albert Einstein and Willem de Sitter. For that reason this simplest model is sometimes associated with their names.

However, in his paper Alexander Friedmann also proposed a more "tragic" solution. He assumed that the mean density of matter in the universe is greater than the critical value. This required abandoning Euclidean space and passing to a spherical, Riemannian three-dimensional space with a variable radius of curvature.

At the beginning — at the notorious "zero point" — nothing distinguished this model from the previous one.

But afterwards events unfolded differently. The radius of the non-Euclidean spherical space, as the next diagram would show, did not increase without limit. At a certain point, *M*, it reached a maximum and then began to decrease again to zero.

This meant that in the history of the expanding universe there must come a moment when the recession stops, after which everything proceeds in the opposite direction. Contraction begins. After some time planets, stars and galaxies merge once more into a single lump of primordial matter. This model came to be called the *closed universe*.

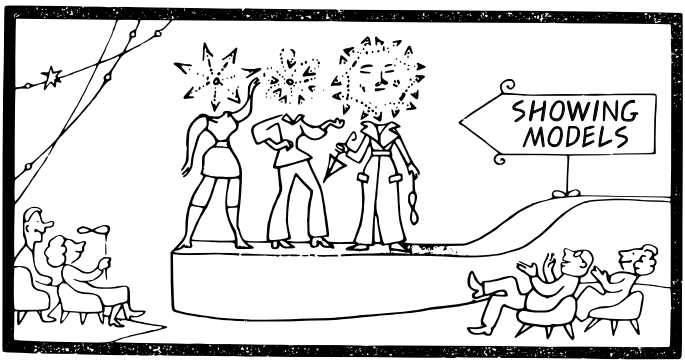
In 1924 Alexander Friedmann published a new paper devoted to Einstein's theory. It was entitled *On the Possibility of a World with Constant Negative Curvature*. In it he examined Einstein's equations under the assumption that the mean density of matter in the universe is less than the critical value.

The result was a new model with non-Euclidean geometry — an unlimitedly expanding space of negative curvature. The hyperbolic space of Nikolai Lobachevsky, which had provoked so much ridicule during the lifetime of the great geometer, received the right to exist alongside Euclidean and Riemannian space. The radius of Lobachevskian space increased somewhat faster than in the first model.

Thus there were three Friedmann models of the uni-

verse. All begin with a zero radius. All expand. Two of them assert a non-zero curvature of space.

Yet how are we to believe these theoretical constructions? How can we be convinced that the universe, which humanity for centuries has seen as unchanging, is in fact in a state of continual motion and expansion? How are we to understand that, however distant in the past, there was a moment when the whole world was compressed into a point — the beginning of everything, even of time itself? And how can we determine whether the space around us possesses curvature? Finally, which of Friedmann's three models is closest to objective reality?



These questions quite literally deprived theorists of sleep. Not only physicists, astronomers and mathematicians were drawn into the debate. The controversy grew especially sharp when philosophers entered it, followed by theologians unwilling to miss the opportunity to speak

about science from the standpoint of religion.

If the reader's patience has not yet been exhausted, the author is pleased to say that the following chapters will be devoted precisely to resolving these doubts and questions.

8.3 Yet Another Great Discovery

The story of the discovery discussed in this chapter began in 1912, when the American astronomer Vesto Melvin Slipher undertook a study of the spectra of nebulae at Lowell Observatory.

At that time no one knew exactly what these strange misty patches in the sky really were — actual clouds of gas or clusters of unimaginably distant stars. There was no certainty either about how far away these faint objects were, or whether they belonged to our Galaxy or lay beyond its boundaries.

Nevertheless, when he began his work, Slipher had a definite expectation concerning the spectra of nebulae. He believed that roughly half of the observed objects should show a shift towards the red end of the spectrum, and half towards the violet.

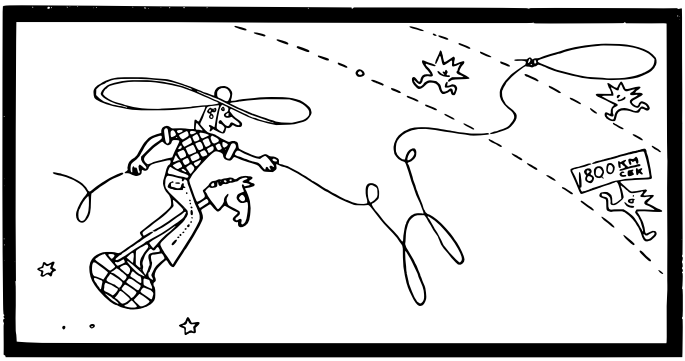
The reason for such shifts was explained by the Doppler effect. The essence of this phenomenon is that, at sufficiently high velocities of a light source — in this case a nebula — the frequency of the electromagnetic waves

perceived by an observer increases when the source approaches and decreases when it recedes.

It follows that if a nebular patch is moving towards the Earth, the wavelength of its light must become shorter. Its spectral lines will appear shifted towards the violet region. If, on the contrary, the nebula is moving away from the Earth, the opposite occurs: the lines of its spectrum are displaced towards the red region of longer wavelengths.

This shift was measured in relative terms and defined as the ratio of the change in wavelength to the emitted wavelength ($Z = \Delta\lambda/\lambda$).

The physicist George Gamow used to tell a humorous story in his lectures to help students remember the rule of the Doppler effect. The anecdote concerned his colleague, the well-known American physicist Robert W. Wood.



Once, in Baltimore, Wood was stopped by the police

for driving through a red light. In court the distinguished physicist brilliantly argued that, owing to the Doppler effect and the high speed of his motor car, the red light had shifted towards the violet end of the spectrum and had become green. Therefore, as a driver, he was not at fault. The judge was already inclined to acquit him. But, unfortunately for Wood, a student whom he had recently failed in an examination happened to be present in the courtroom. The student quickly calculated the speed required to turn red light into green. The judge then abandoned the original charge and fined Wood for exceeding the speed limit.

When he began his observations, Vesto Melvin Slipher reasoned as follows: since there can be no preferred direction in space, roughly half of the nebulae should be receding from us and half approaching. One may imagine his disappointment when careful measurements showed that, of seventeen observed nebulae, only two — judging by their violet shift — were approaching the Earth. All the others exhibited a red shift and were therefore moving away from us.

The determination of radial velocities from spectral shifts was regarded as painstaking and, apparently, not especially promising work. For almost ten years Vesto Melvin Slipher remained virtually the only astronomer engaged in it.

By the beginning of the 1920s he had measured the spectral shift and calculated the velocities of forty-one nebular objects. Almost all of them were receding. The

radial velocities derived from the red shift ranged from 300 to 1800 kilometres per second — far exceeding the highest stellar velocities known at that time.

To suppose that an entire class of objects within the Galaxy was moving away from us would have meant attributing some special status both to that class and to our own Solar System.

The puzzling behaviour of Slipher's nebulae attracted the attention of two other astronomers: Milton Humason, who had begun his career as a caretaker at an observatory, and the staff observer Edwin Hubble. Indeed, Hubble was perhaps even more than Humason an astronomer by vocation. After graduating from the University of Chicago with a degree in law, he entered Yerkes Observatory at the age of twenty-five and became an observational astronomer. To change one's profession so decisively in the twentieth century required not only courage but genuine calling.

By that time the largest telescope in the world had come into operation at Mount Wilson Observatory, equipped with a mirror two and a half metres in diameter. Hubble and Humason began meticulous work, photographing faint nebulae with exposures lasting many hours, sometimes even days. Their technical skill was exceptional. And the day came when, for the first time in the history of astronomy, they succeeded in resolving stars in the Andromeda nebula.

So the nebulae did indeed consist of stars. They were unresolved simply because they lay at enormous distances

from us, beyond the limits of our own stellar system — our Galaxy. For that reason these remote objects were first called extragalactic nebulae.

The proof of their stellar nature was such a major step forward that the English astronomer Harlow Shapley proposed that extragalactic nebulae should be renamed "galaxies". This emphasised the vast enlargement of the universe, now understood to consist of numerous stellar islands similar to our own.

Edwin Hubble devoted almost his entire life to the study of these extragalactic nebulae — galaxies — extending the boundaries of the known universe to distances of a billion light-years. In the final decades of his life he undertook the task of classifying them and compiling a systematic catalogue. By 1953, the year of his death, his classification was largely complete and included about a thousand of the brightest galaxies of the northern and partly the southern sky.

In 1928, while photographing the spectrum of one of the faintest and most distant nebular objects, Milton Humason made an exceptionally long exposure. When the plate was developed, Hubble and Humason examined it carefully. They could scarcely believe their eyes. The galaxy listed in the Dreyer catalogue as NGC 7619 showed such a large red shift that its calculated velocity amounted to 3,800 kilometres per second — an astonishing value for a celestial object at that time. From that moment Hubble began to study the spectral behaviour of extragalactic objects with

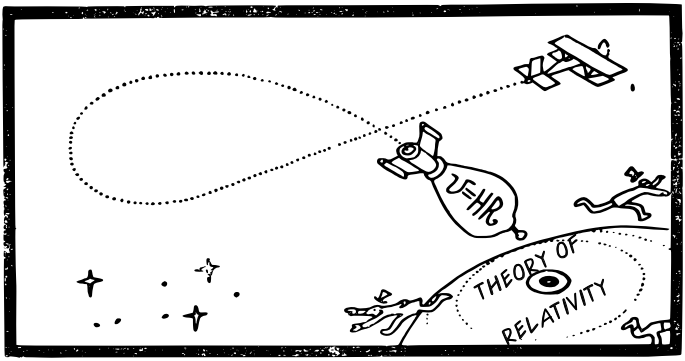
even greater attention.

Gradually, as observational results accumulated, the peculiar feature mentioned earlier was confirmed: almost all galaxies, with only minor exceptions, exhibited a red shift. This meant that they were receding from our stellar system. Moreover, *the faintest galaxies* — those most distant from us — *showed the largest spectral shifts*.

The conclusion suggested itself: *distant stellar systems are moving away with greater velocities than those nearer to us*.

By 1929 Edwin Hubble announced that he had established a fundamental relationship: the red shift in the spectra of galaxies, expressed as $\alpha = \Delta\lambda/\lambda$, is proportional to the distance to the galaxies.

This was a discovery of immense significance. It provided striking support for the expanding-universe hypothesis proposed by Alexander Friedmann.



If the red shift of distant galaxies is indeed a consequence of the Doppler effect — that is, caused by their recessional velocity — then galaxies must recede at speeds proportional to their distances:

$$v = H \cdot r.$$

Here H is a proportionality coefficient with the dimension of inverse time.

For convenience, to avoid unwieldy numbers, H is usually expressed in units of kilometres per second per megaparsec:

$$H = \text{km s}^{-1}, \text{Mpc}^{-1}$$

A megaparsec (Mpc) corresponds to a distance of approximately $3.084 \cdot 10^{19}$ kilometres.

The letter H — *the Hubble constant* — was chosen deliberately, in honour of Hubble, whose name was given both to this fundamental law of the universe and to the constant itself.

It now remained to determine the value of the coefficient H, since it fixes the time T that has elapsed from the mysterious "zero point" to the present epoch. For most Friedmann models the time scale is, in order of magnitude, inversely proportional to H:

$$T \approx \frac{1}{H}.$$

However, obtaining a reliable value for this cosmic constant proved far from simple. Only by 1936 did Edwin

Hubble conclude that

$$H = 540 \text{ km s}^{-1}, \text{Mpc}^{-1}.$$

From this value one obtained the lifetime of the universe:

$$\begin{aligned} T &= \frac{1 \text{ Mpc}}{540 \text{ km s}^{-1}} \\ &= \frac{3.084 \cdot 10^{19} \text{ km}}{540 \text{ km s}^{-1}} \\ &= 5.72 \cdot 10^{16} \text{ s} \approx 1.8 \cdot 10^{9} \text{ years} \end{aligned}$$

That is, roughly two billion years.

But geological data already indicated that the age of the Earth exceeded two and a half billion years. Could our planet have formed before the universe itself?

Opponents of the Friedmann models attempted to use this apparent absurdity to undermine confidence in the new cosmology. Supporters of general relativity maintained that the discrepancy arose from inaccurate distance measurements to galaxies. As Max Born remarked, this "strange fact gave rise to much speculation".

The discovery of red shifts allowed some adherents of the Einstein–Friedmann framework to celebrate what they regarded as experimental confirmation. Others, however, began to question not only the expanding-universe model but even the broader conclusions of general relativity. Doubts were raised about interpreting the red shift as a Doppler effect. Alternative explanations for the observed phenomenon were urgently sought.

One hypothesis, which enjoyed considerable popularity at the time, proposed that particles of light — photons — lose part of their energy while travelling through the universe.

The energy of a photon is proportional to its frequency and therefore inversely proportional to its wavelength:

$$E = h\nu = \frac{hc}{\lambda}.$$

If the energy decreases, the wavelength λ must increase. Consequently, the entire spectrum of a distant object would be shifted towards the red. In this picture there is no expansion at all. The magnitude of the spectral shift would simply be proportional to the distance travelled by the light.

Some twenty years ago this hypothesis was seriously discussed at theoretical symposia. But it eventually became clear that it required abandoning one of the fundamental laws of nature — the conservation of energy.

If photons lose energy without transferring it anywhere, the conservation principle is plainly violated. If, on the other hand, photons transfer part of their energy to some medium or to other photons, their paths must be deflected. In that case the images of distant galaxies could not remain sharp. The greater the distance, the more blurred the images should appear. Yet even the faintest and most remote galaxies are recorded on astronomical plates with outlines as sharp as those of the nearest stellar systems.

A second hypothesis suggested that a photon might spontaneously split into a lower-energy photon and some additional particles. Why should this occur? No clear reason was offered — it was simply assumed to happen during very long journeys.

This idea was sharply criticised by the young and gifted Soviet theoretical physicist Matvei Bronstein. Working alongside Lev Landau, he was among the first in his country to address the problem of quantum gravity and effectively laid its foundations. He would undoubtedly have become a scientist of outstanding stature had his life not been tragically cut short in 1938.

Criticising the photon-decay hypothesis, Matvei Bronstein showed that, if light quanta possessed such a property, different parts of the spectrum of a single object would exhibit different red shifts. Moreover, the spectral lines would inevitably broaden. Radio waves from distant sources would not reach us at all — they would disintegrate during their journey.

In the end, specialists and sceptics alike were forced to concede that no interpretation of the red shift other than the cosmological one — based on the Doppler effect — was viable. To this day there is no acceptable hypothesis that explains the three principal properties of the red shift in any other way. These properties are:

1. Independence of the red shift from the wavelength of the spectrum.

2. The Hubble law:

$$v = H \cdot r.$$

3. Isotropy of the red shift, that is, its independence from direction.

One objection nevertheless remained: the discrepancy between the age of the universe calculated from Hubble's data and the geological age of the Earth. For nearly twenty years astronomers tolerated this difficulty. For two decades the Earth appeared older than the universe.

Only at the end of the 1950s did a new generation of astronomers revise the extragalactic distance scale. As a result, the Hubble constant H turned out to be six to seven times smaller than the value originally determined by Edwin Hubble.

Today one often adopts

$$H = 75\nabla \cdot 100 \text{ km s}^{-1}, \text{Mpc}^{-1}$$

With this revised value, the age of the universe becomes

$$\begin{aligned} T &= \frac{1}{H} \\ &= \frac{1 \text{ Mpc}}{(100\nabla \cdot 75)\text{km s}^{-1}} \\ &= \frac{3.086 \cdot 10^{19} \text{ km}}{(100\nabla \cdot 75)\text{km s}^{-1}} \\ &\approx (10\nabla \cdot 13) \cdot 10^{9} \text{ years} \end{aligned}$$

Thus the lifetime of the universe is of the order of ten to thirteen billion years — a value consistent with geological and astrophysical evidence.[34]

The time has now come to attempt to determine the horizons of the world that surrounds us.

8.4 Horizons of the Universe

People long ago noticed that celestial bodies tend to unite into systems. The first such system familiar to us is the Earth–Moon pair.

Saturn, encircled by its remarkable ring, has numerous satellites. Jupiter possesses even more. Our Sun — regarded as an ordinary star among countless others — has a system of planets and their moons.

And the stars themselves — into what systems do they combine?

Stars form binary, triple and multiple systems. On a larger scale there are open star clusters, containing from dozens and hundreds up to a few thousand stars. Even more impressive are globular clusters, which sometimes include more than a million stars.

Academician Viktor Ambartsumian discovered yet another type of stellar grouping — associations of young, hot stars. All these communities belong to a vast stellar system

[34] Since this was written, the precision of the Hubble constant (H_0) has improved significantly. As of 2026, measurements from the Planck satellite (Early Universe) suggest a value of approximately 67.4 km/(s Mpc), while local measurements using Type Ia supernovae suggest approximately 73.0 km/(s Mpc). This "Hubble Tension" remains one of the most significant puzzles in modern cosmology. These values imply a Hubble time ($1/H_0$) of roughly 13.4 to 14.5 $\times 10^9$ years. When adjusted for dark energy and matter density within the ΛCDM model, the age of the universe is determined to be $13.787 \pm 0.020 \times 10^9$ years. Also, look at the last chapter which summarises many present day (c. 2026) aspects of cosmology. – DM

known as the Galaxy, comprising roughly one hundred billion members.

The first to describe the Galaxy in a genuinely scientific and convincing manner was William Herschel. He explained that all observable stars form a gigantic stellar system shaped somewhat like a lens. This system came to be called the Galaxy. Yet for a long time this idea remained only a hypothesis.

In the 1920s Edwin Hubble demonstrated that spiral and certain other faint nebular patches, barely discernible even on photographs taken with powerful instruments, are in fact remote stellar systems comparable in size with our own Galaxy. A new epoch in astronomy began.

The radius of the observable world increased tens of thousands of times. Such a quantitative enlargement of the horizon inevitably led to qualitative changes in our understanding of cosmic objects. In the universe nothing appears to be unique, yet nature does not produce its creations on a conveyor belt either. Galaxies, radio galaxies, quasars, quasi-stellar objects, pulsars — who can say what awaits astronomers whenever more powerful telescopes come into operation?

Our Galaxy is surrounded by about sixteen neighbouring galaxies forming a fairly compact group known as the *Local Group*. Astronomers consider that all seventeen known members of this group are connected not only by physical laws common to the system as a whole, but also by a common origin.

Observing millions of galaxies scattered across almost every region of the sky, astronomers have noticed that galaxies themselves tend to cluster, forming *galaxy clusters*. By analogy with stars, one may reasonably ask: "Do clusters of galaxies in turn combine into still larger superstructures?"

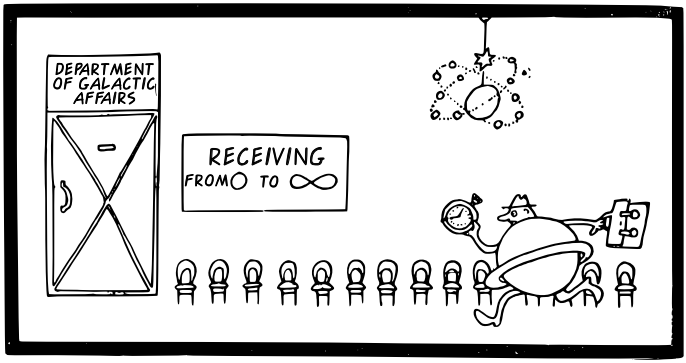
In 1953 the French astronomer Gérard de Vaucouleurs expressed the view that the brightest galaxies (up to 12th apparent magnitude), that is, those closest to us, are distinctly concentrated, forming a colossal flattened system, which he called a *supercluster of galaxies*. At the same time the Soviet astronomer Boris Vorontsov-Velyaminov discovered that not all observed galaxies belong to this supercluster. This means that it is not a metagalaxy encompassing all objects within the limits accessible to observation.

This gives rise to the question: "Might the next level in the organisation of matter in the universe be regarded as the metagalaxy?"

There appear to be no directly observable facts to justify such a conclusion as yet. And yet there are certain grounds for supposing that a system such as the metagalaxy does exist.

There is a somewhat vague assumption that the metagalaxy contains approximately as many giant stellar islands as a galaxy like ours contains stars, and that the metagalaxy is an autonomous system of galaxies. The dimensions of the metagalaxy are not difficult to calculate if one accepts

the Hubble law in advance. Strictly speaking, it is not entirely accurate at very great distances. But let us disregard this circumstance. Then the boundaries of the observable universe would be pushed out to the distance at which galaxies are receding from us with the velocity of light c.



Thus, the Hubble law: $v = H \cdot r$. Hence, if $v = 300,000$ km/sec, then

$$r = \frac{v}{H} = \frac{300,000 \text{ km/sec}}{(100 \nabla \cdot 75) \text{ km/sec} \cdot \text{Mpc}}$$
$$= (3000 \nabla \cdot 4000) \text{ Mpc}.$$

One cannot even say that this is an "enormous" distance. It is simply an inconceivable distance of 10^{28} centimetres, which there is no point in converting into kilometres. In any case, it cannot be imagined.

There is a supposition that the metagalaxy is not the

final stage in the organisation of matter in the universe. But if the metagalaxy is not the whole universe, one may reasonably ask: what then lies beyond?

And beyond, some scientists say, one must apparently "assume the existence of other metagalaxies at still greater distances and, perhaps, with even more grandiose schemes of organisation."

"Well, that is splendid!" the reader is entitled to exclaim. "Does it not seem to the author that the 'demon of infinity,' banished from the very first pages, has smuggled itself back into the picture of the world?"

What can the author reply? He will spread his hands in dismay and mutter something indistinct, referring to the spiral path of the development of knowledge and to a new, ever higher level of our understanding of infinity — not only in comparison with the Greeks and the Arabs, but also with the conceptions of Isaac Newton and Nikolai Lobachevsky, Bernhard Riemann, Albert Einstein and Alexander Friedmann.

8.5 Father Georges Solves Equations

"I merely solve the equations. It is for the physicists to interpret their physical meaning." These words are attributed, with some uncertainty, to Alexander Friedmann. The point is that the "Friedmann universes" expanded because the

solutions of Albert Einstein's cosmological equations required them to do so. That was all.

Half a century ago this did not appear nearly so evident as it may seem to us from the standpoint of 1971. People longed to see a physical picture of the birth of the universe corresponding to the abstract mathematical scheme. They demanded an interpretation of the mathematical solutions.

In 1931 the professor of the University of Louvain in Belgium, Abbé Georges Lemaître (1894–1966), proposed that the "zero point" of the universe should be regarded precisely as the moment when all substance, all the matter of the universe, was hurled in different directions from a tiny volume tending, at the "zero point" of space and time, towards zero. For some, this hypothesis once again smacked of "creation of the world". Something from nothing! Only the Lord God, it was said, could perform such miracles.

It is difficult to find detailed information about Georges Lemaître, although he firmly ranks among the foremost cosmologists working in relativity theory. The reason, evidently, lies in the dual character of his life and destiny.

In 1922 the twenty-eight-year-old Lemaître was ordained as a priest. In 1923–1924 he studied astrophysics intensively at University of Cambridge and at the Massachusetts Institute of Technology. There he also defended his dissertation. In 1927 Lemaître returned to Belgium, where he became professor of astronomy at the Catholic University of Louvain.

Lemaître devoted much effort to the general theory of relativity. Approximately ninety per cent of all his works (he published seventy-three papers) were devoted to relativistic cosmology and to problems of general relativity.

In 1931 Georges Lemaître was the first to give a vivid description of how all the matter of the universe had once been compressed into a single lump, which he called the "primeval atom", and how at one fine moment, $t = 0$, the "primeval atom" exploded. Its fragments, the original clump of matter, flew apart (and continue to fly apart even now) in different directions, giving rise to the observable universe with all the attributes of its space-time.

Lemaître's model was easy to grasp and highly impressive. His solution differed slightly from that of Alexander Friedmann. The radius of curvature changed with time, as it were, with a "pause". At the same time Lemaître himself, understanding the weakness of the "creator hypothesis", treated it with great caution and was far removed from any primitive notion of a wonder-working God who created the world out of nothing. Here is what he said concerning the theory of the expanding universe with a "beginning" at the Eleventh Solvay International Congress in 1958, devoted to problems of cosmology:

"Insofar as I can judge, such a theory remains entirely apart from any metaphysical or religious questions. It leaves the materialist free to deny any transcendent being. With regard to the beginning of space-time, the materialist may remain of the same opinion that he might hold in the

case of non-singular regions of space-time."

Thus Lemaître, though he was an abbé — Father Georges — sought not to confuse questions of faith with those of knowledge. Yet it is hardly likely that our reader will be greatly interested in the problem of a clergyman's relations with his idol. Our task is different.

As a scientist, Georges Lemaître was unquestionably an outstanding figure. An honorary doctor of several universities, a member of the Belgian and Italian Academies of Sciences, he also became a member of the Pontifical Academy of Sciences in the Vatican and in his later years was elected its president.

One of the very few scientists in the world, Lemaître was awarded the Eddington Medal in 1953.

8.6 An International Prize for the Popularisation of Scientific Ideas to Georgy Gamow

In its time Lemaître's model played a very significant role in the development of scientific outlook. It became especially popular after the physicist George Gamow (1904–1968) called Lemaître's theory the *Big Bang Theory* and further developed its initial stage.

The figure of Georgy Antonovich Gamow is a controver-

sial one. The author might perhaps not have mentioned his biography at all, confining himself to an account of the theory, were it not for the scientist's death, which brought a sad yet inevitable conclusion to the life he chose for himself.

Georgy Gamow was born in Odessa. There he began his studies and observed the stars through a telescope given to him by his father; in Odessa he also completed secondary school. After celebrating this event, the young man entered Leningrad State University. His student years coincided with the period of rapid formation of Soviet physics. It was this period that gave our country Pyotr Kapitsa and Nikolay Semyonov, Igor Kurchatov and Yulii Khariton, Vladimir Kondratyev and Anatoly Alexandrov, Isaak Kikoin and many other prominent scientists of our time. Today this older generation of Soviet physicists includes Nobel Prize laureates, Lenin Prize laureates, and, above all, people whose names are known and spoken with respect by the people of their native country.

With many of them Georgy Gamow began his career; he knew them, argued with them, and worked alongside them. In 1928 he defended his dissertation and was sent, as part of a group of talented young scientists, to a summer school in Göttingen — the "Mecca of science" at the beginning of the century. He then continued his work at the Cavendish Laboratory under Ernest Rutherford and James Chadwick. In Copenhagen he met Niels Bohr, to whom he spoke about his work on quantum theory and nuclear structure. Bohr invited him to spend a year at his Institute of Theoretical

Physics and secured for him a scholarship from the Royal Danish Academy of Sciences.

A brilliant scientific career, immense talent, and dazzling prospects lay before him. In 1931 Gamow returned to the USSR and was elected a corresponding member of the Academy of Sciences of the USSR — at only twenty-seven years of age.

But then came 1933. Together with other Soviet scientists, George Gamow travelled to the Solvay Congress in Brussels, where he received an invitation to deliver a series of lectures on nuclear physics at the University of Michigan.

After a short stay in France at the Pierre Curie Institute, he moved to the United States, where he began permanent work as Professor of Physics at George Washington University in Washington. There, in collaboration with the Hungarian émigré Edward Teller, he developed his famous theory of beta decay. He then published a number of works on the theory of nuclear liquid and on nuclear reactions in stars. Together with Schoenberg he developed the theory of the "Urca process", which drew specialists' attention to the role of neutrinos in stellar processes. (Gamow, a native of Odessa, could not resist introducing a piece of slang to designate processes involving the "theft" of energy. Thus the "urki" acquired citizenship in scientific literature.)[35] Here too he began to develop a theory of the formation of the elements.

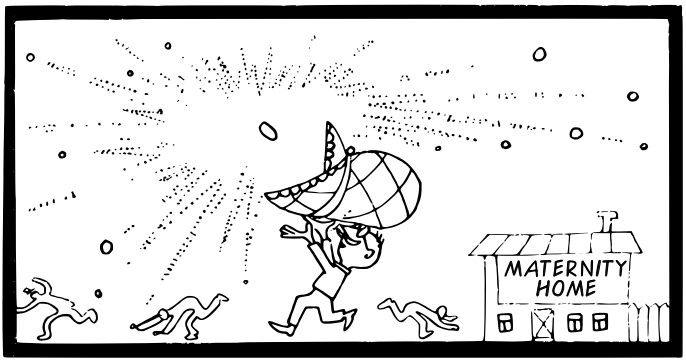
America's entry into the Second World War did not

[35] The name alludes humorously to the Casino da Urca in Rio de Janeiro, where money was said to disappear just as quickly. – DM

alter Gamow's interests. He became a scientific consultant to a number of military institutions and took part in the Manhattan Project, advising the Los Alamos group directly engaged in the creation of the atomic bomb.

Later his joint work with Teller helped the Americans construct and detonate their first hydrogen monster. It was perhaps then that the crest of regret rose especially high in his soul. Neither his own departure — Gamow had been one of the leading Soviet physicists of the 1930s — nor the war, won by his native but abandoned people, halted the development of science. Had he not left, that process might perhaps have proceeded even faster.

At the time when the Americans were still assembling their cumbersome installation for producing a hydrogen explosion, in the Soviet Union the hydrogen bomb had already been completed, tested, and put into serial production.



After the war George Gamow withdrew from nuclear physics. Echoes of his earlier work were still heard in the cosmological hypothesis of the Big Bang which he developed in 1947–1949. But in 1954 he sharply changed the direction of his research and turned to questions of biology. Here again there was a flash of genius — Gamow proposed the idea of the genetic code and published a whole series of pioneering works in biology.

In 1956 he moved to the University of Colorado, where he remained until the end of his life.

On 20 August 1968 Georgy Antonovich Gamow passed away. Having moved to the United States, he severed all ties with his homeland and became fully naturalised. Yet to the end of his life he remained Russian, longed for Russia, and died lonely and sorrowful — the usual fate of an émigré. Whatever a person's talent, intellect, or other qualities, there is no more bitter fate than to lose one's homeland, even if outwardly his life appears a parade of prosperity.

In America Gamow devoted much effort to the popularisation of science. He wrote more than a hundred scientific papers and about thirty popular science articles. Around thirty volumes of his books were published, twenty-three of them devoted to popular science. Gamow was a member of many academies throughout the world, and in 1956 the United Nations awarded him the International Prize for Outstanding Contribution to the Popularisation of Scientific Ideas. Such recognition is rare indeed; one must truly be an outstanding populariser to receive such an honour

in our world.

In any case, the reader may acquaint himself with an example of G. A. Gamow's style of popular thinking in the following section.

8.7 "Big Bang", or the "Great Explosion", in the Science of the Origin of the Universe

Thus, you will recall, the Abbé Georges Lemaître put forward the idea of the "birth" of the universe. At the same time he prudently did not extend the curve of the changing radius of curvature all the way to the origin of coordinates. He even preferred to draw the axes with a break at this "singular" point. No — Professor Lemaître preferred not to speak at all about the initial period in the development of the universe.

George Gamow was interested precisely in the beginning. He was not satisfied with the name "primeval atom". He preferred to call the lump of primary, densely compressed and incandescent primordial matter, existing in a "pre-explosive" state, *ylem*, borrowing this term from Aristotle. (The philosopher of Stagira used it to denote the fundamental substance of the universe.)

In Gamow's view, the evolution of the universe may be divided into five stages. At first the ylem consisted of

a highly compressed mass of hydrogen, in which all the electrons of the atomic shells had been pressed into the protons of the nuclei; the neutrons formed in this process were compressed to the limit, producing a homogeneous mass of colossal density, and at an extremely high temperature.

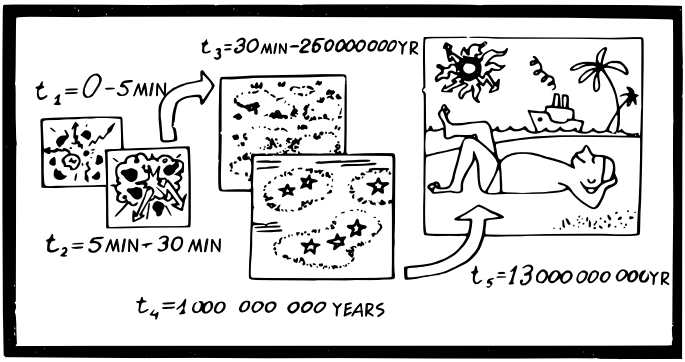
In 1948 Gamow, together with his co-authors R. Alpher and H. Bethe — whose surnames conveniently formed the beginning of the Greek alphabet — presented the "alpha, beta, gamma theory" of the formation of the elements as a result of the explosion of the ylem. (For the sake of accuracy it should be said that Bethe took no part in this work; his name was required by Gamow for the elegance of the title.)

This theory assumed that the ylem flew apart literally into individual neutrons. Under the infernal conditions that prevailed, the neutrons rapidly decayed into electrons and protons.

Look at the diagrams. They show five stages, or five episodes, from the history of Gamow's universe. Each is marked with the time during which the curtain was raised.

Thus, the first act — from 0 to 5 minutes after the "beginning". The ylem has just exploded. In the scene you see a mixture of particles. Phlegmatic neutrons, unable to withstand the monstrous temperatures, decay into protons and electrons, accompanied by nimble photons. In such an "atmosphere", despite the "crowding", the particles move with energies comparable to those of modern accel-

erators. Within the depths of the ylem nuclear reactions boil furiously — particles collide, forming nuclei of light elements, which immediately break apart



The second act — from the fifth minute to half an hour of newly born time. This is no longer ylem, yet not quite the universe. As expansion proceeds, the temperature falls. One may suppose that such a process is no novelty to the well-informed reader. Recall — this is nothing other than the familiar operating principle of an ordinary refrigerator.

Half an hour of continuous explosion is sufficient to prepare the main supply of building material for all further work. The reader, of course, knows that free neutrons have a half-life of only 12–13 minutes. After half an hour too few remain for reactions to proceed with their former ease. Together with protons, neutrons form deuterons and tritons, nuclei of helium and other heavier elements. Thirty minutes later, of the original number of neutrons

there remains approximately one-eighth ... The synthesis reactions fade away ...

The next, third act occupies the period from the thirtieth minute of the "performance" to the two-hundred-and-fiftieth millionth year of existence. The author hopes that the reader understands how much trust should be placed in the figures cited. A hypothesis is a hypothesis, and the most its creator can claim is an approximate order of magnitude ...

Thus, half an hour after the explosion, the newly formed nuclei began to capture homeless electrons and to form atoms. The atoms gathered into clouds, which later gave rise to galaxies and stars. This period George Gamow characterises as the emergence of the protogalaxy ...

The fourth act — the first billion years draw to a close. Galaxies have arisen in the universe, within whose depths protostars are born and, perhaps, even protoplanets.

And finally, the last act covered the following four billion years and ended in our own time. Altogether this amounted to roughly five billion years! The attentive reader, however, should not be surprised, for he will recall that in the 1960s the time scale was revised upwards, and five billion years of the universe were transformed into thirteen! This fact will find its place in our book in due course. Unfortunately, the complex and tangled history of cosmology does not allow all events to be arranged in strict chronological order. Digressions and anticipations are as inevitable as certain repetitions.

The vividness of the hypotheses of Georges Lemaître and George Gamow attracted universal attention. In the opinion of many supporters of the hypothesis, such an explosion must in some way resemble the explosion of an atomic or hydrogen bomb — only, of course, a super-bomb, a super-super-ultra-bomb, and so on, a bomb impossible to imagine, quite beyond even the most extravagant fantasy. This comparison, born in the period of the "atomic-hydrogen boom", spread among the widest circles. It may be that the reason for this comparison lay in the fact that physicists who had taken part in the development of hydrogen weapons were among the most ardent supporters of the "big bang" hypothesis.

Of course, the singularity inherent in this model troubled everyone — that notorious special point, or zero-point, of the universe. It was also troubling that so much attention in the hypothesis was devoted to the first thirty minutes after the explosion. After all, the age of the universe amounts to billions of years ... On this matter it is appropriate to give the floor to the author of the theory himself.

> "Many people," reflects Gamow, "consider that it has no physical meaning to speak of a half-hour or an hour that occurred 5 (now, according to the new scale, 10–13 — A.T.) billion years ago. In reply I suggest: let us look at the place in Nevada where an atomic bomb was exploded several years ago. That place is still 'hot' because of the existence of long-lived products of the explosion. To create those products required only a millionth of a second. Simple arithmetic shows that the period which has

> passed since that explosion exceeds a microsecond by the same factor as 5 (respectively read 10–13 — A.T.) billion years exceeds 'that' half-hour! Yet this difference does not make the moment of the explosion any less interesting or less significant for us."

If everything occurred precisely as George Gamow supposed, then even today it should be possible to find somewhere in the universe traces of the colossal temperatures that prevailed in the first moments of the "big bang" ... Let them be only the "cooled remnants" of some primordial quanta ...

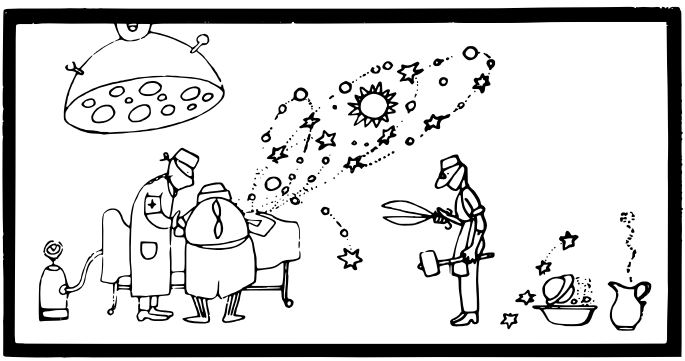
While matter remained in an ionised state, it constituted a hot plasma of electrons, protons, and nuclei of light elements (chiefly helium).

At first this plasma was in dynamic equilibrium. This means that the particles emitted and absorbed equal quantities of quanta of electromagnetic energy. The temperature of the radiation was in complete correspondence with the temperature of the plasma. But gradually the distances between the particles increased. (After all, the explosion imparted to them enormous velocities of recession.) Now, for an emitted quantum of energy to reach a particle capable of absorbing it required time. In transit the energy of the quantum decreased.

Thus, with the expansion of the universe the temperature of the radiation falls. The farther a quantum must travel, the "colder" it becomes. (Recall that the redshift

from distant galaxies is greater than that from nearby ones.)

A few hundred thousand years after the "beginning", the temperature of the considerably "rarefied" medium fell to approximately three to four thousand degrees. Now not all emitted quanta were absorbed by excited particles. The medium became "transparent" to radiation; it, as it were, "detached" itself and began to "wander" through the universe. It is these electromagnetic waves that ought to have survived to our own day, though "aged" and "cooled". Calculations by theorists showed that, by the time they reached us, this radiation should have a temperature no higher than three to four degrees Kelvin.



Thus the "hot" model of Gamow required that in our own time radiation at 3–4°K should be detectable in the universe. In 1948 no means yet existed for such observations. In the post-war years radio astronomy was only beginning its rapid advance, and the measurement of radiation of

such low temperature seemed to radio astronomers of that period an entirely hopeless undertaking.

In the middle of the twentieth century — as at other times when humanity was not engaged on battlefields — the Second World War gave way to the "Cold War". Questions concerning the origin of the universe once again found themselves at the centre of fierce ideological struggle.

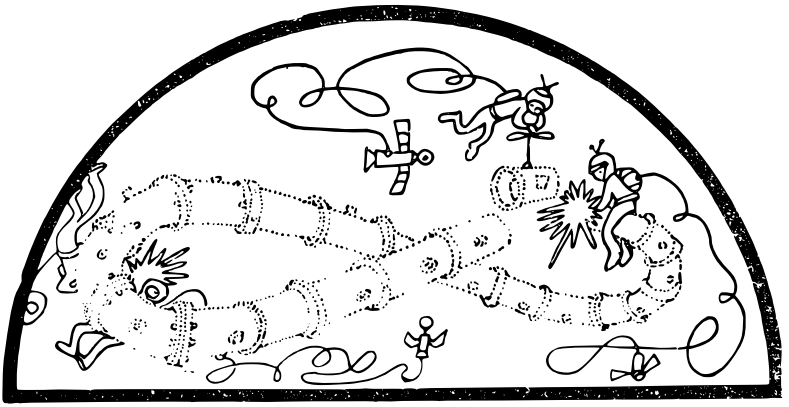
One of the most influential currents of idealist philosophy was Neo-Thomism. The Neo-Thomists made wide use of the principle of the harmony of reason and faith, introduced by Thomas Aquinas in the thirteenth century, eagerly employing unresolved scientific questions in defence of religious dogma. It is no accident that in 1879 Neo-Thomism was proclaimed the official philosophical doctrine of the Catholic Church. And in 1951 Pope Pius XII delivered a major address calling for the achievements of modern science to be recognised as proofs of the omnipotence of God.

A number of scientists representing the materialist tendency hastened to dissociate themselves decisively from idealist trends in cosmology and ... fell into the opposite extreme. Together with God they renounced the entire theory of the expanding universe. For quite a long time among materialists it was considered "good form" to remain faithful to the idea of an infinite universe, while relativistic cosmology was declared a "barren mathematical game devoid of any astronomical significance"; the general theory

of relativity, for its part, was regarded as "mathematical exercises having nothing in common with cosmology".

Thus disputes about models of the world became intertwined with disputes about the world-views of two irreconcilable camps: materialism and idealism.

Meanwhile, before continuing their argument, the opposing sides first had to agree on the very subject of the dispute. For, as it turned out, not all representatives of the rapidly developing science of cosmology attached the same meaning to the term "universe". In short, by the middle of the present century cosmology presented a thoroughly and expertly tangled knot of contradictions. It fell to the scientists of our generation to untie it.



9. A Journey Along the *t*-Axis

In which the reader at last, first, arrives in his own time; second, becomes acquainted with the results of the practical work of astronomers and cosmologists; and third... Thirdly — although this was not quite the author's intention — the reader may discover that all the foregoing has not made matters any simpler.

The sciences that study the universe are remarkable. On the one hand, their methods make it possible to detect differences in the positions of celestial objects measured in fractions of an arcsecond. And alongside this there exist approximations of which it is said that the results are perfectly satisfactory provided they do not differ by more than an order of magnitude...

In recent years cosmology has been moving from the category of purely speculative disciplines into that of the physical sciences. And like every developing branch of knowledge passing through a formative period, it is occupied with refining and reassessing its results. For this reason the author would like to warn the reader that the values of many quantities are not yet final. Different observers still obtain different results from the same investigations, and only gradually do these values approach the truth.

One must remember that every figure in extragalactic astronomy is obtained at the cost of extraordinary effort — at the price of devilishly ingenious theoretical and experimental devices. Yet extragalactic astronomy is one of the principal suppliers of factual material for cosmology.

A reader who has absorbed the idea of the expanding universe should already understand quite clearly that the more distant the observed object, the longer light requires to reach terrestrial telescopes, and consequently the "younger" we see that object to be.

Light and radio waves, which bring us most of our in-

formation about celestial objects, travel through space at roughly 300,000 kilometres per second. The Sun lies eight light-minutes from us. Thus, whenever we look at our star, we see it as it was eight minutes ago. But what if the object under observation is farther away?

Light from Proxima Centauri takes a little over four years to reach the Earth. Consequently, if our Sun’s neighbour were suddenly to go out, we should learn of it only more than four years later.

And what if the observed object is something like the Andromeda Galaxy, situated some two million light-years from us? Then we see it now as it was two million years ago, when the stream of light left its stellar expanses. By examining successively more distant celestial objects, we are, as it were, using a “time machine” to penetrate into the past of our universe.

A “time machine”! Ahead of us still lies a fascinating journey by means of this fantastic mode of transport. Yet imagination has never been an obstacle to science.

9.1 From “Radio Stars” to Star-like Objects

In 1932 the young engineer Karl Jansky discovered radio emission coming from the nucleus of our Galaxy. Then, in 1946, a paper appeared by three British scientists — James Hey, G. S. Parsons, and J. W. Phillips — who detected powerful radio emission from a small region of the sky in the con-

stellation of Cygnus. Thus the first discrete radio source was discovered. Soon other sources followed.

At first, when radio telescopes possessed only modest resolving power, these celestial "radio stations" appeared to occupy very small areas of the sky, like stars. They were therefore regarded as "radio stars". But as the "vision" of radio telescopes became sharper and sharper, observers found that the outlines of the "radio stars" began to blur. Nor did the idea of radio stars accord well with theory. All this led to the abandonment of the radio-star hypothesis.

Many radio sources were initially identified with clouds of gas. Yet it remained unclear whether these "radio clouds" were members of our Galaxy or extragalactic objects. The first discrete radio source to be identified with an optical object beyond the Solar System proved to be located in the Crab Nebula. In 1949 the Australian astronomers John Bolton and Gordon Stanley determined its precise coordinates.

In 1950 the English astronomers Robert Hanbury Brown and Cyril Hazard detected weak radio emission from the Andromeda Galaxy. Yet the "radio stars" had not entirely surrendered their ground.

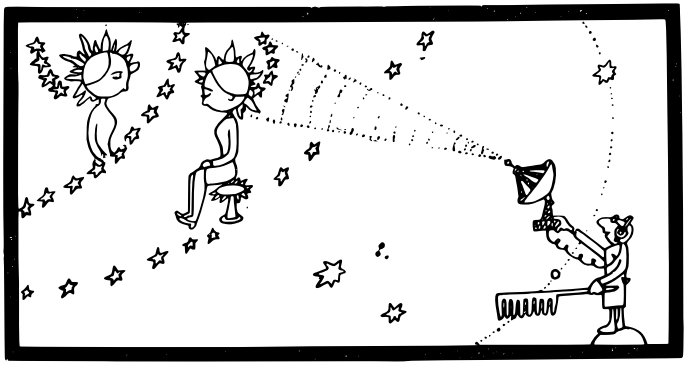
A complete turning point came when Walter Baade succeeded in identifying the first source, Cygnus A, with an optical object situated half a billion light-years away. In outline this object resembles a figure eight, each half of which is a galaxy. From this arose the hypothesis that cosmic radio emission is the result of collisions between distant

galaxies. But what mechanism could produce such enormous energy output? Many suggestions were advanced.

The most fruitful proved to be the theory of the Soviet scientists Vitali Ginzburg and Iosif Shklovsky, according to which the radiation arises from the motion of extremely high-energy electrons in a magnetic field. This hypothesis later received the name "synchrotron radiation" and is now widely used in explaining cosmic emission.

At the end of the 1950s theoretical physicists began to consider what processes might produce electrons of such enormous energies. Calculations showed that nearly one hundred per cent of the energy of a collision between two galaxies would have to be converted into the energy of electrons. Yet laboratory collisions studied in the best particle accelerators yielded only about one per cent of the collision energy in the form of radiation. And in the laboratory the processes were carefully directed by experimenters and were not nearly so chaotic as in space.

Plainly something was amiss with the collision hypothesis itself. Academician Viktor Ambartsumian, developing the theory of explosions in galactic nuclei as a natural phase in their evolution, subjected the hypothesis of colliding galaxies to decisive criticism.



And finally, the last blow to the hypothesis of colliding galaxies was delivered in 1960. The astronomers Thomas A. Matthews and Maarten Schmidt of the California Institute of Technology identified most radio sources with single galaxies.

Around this time work began at the Jodrell Bank Observatory on a programme to measure the angular sizes of celestial radio sources. The British astronomers examined some three hundred radio objects. A radio telescope with high resolving power revealed the existence of sources of extraordinarily small angular size — down to one second of arc and even less.

This discovery seemed to revive the buried idea of "radio stars", and until the end of 1962 it was believed that nothing other than star-like objects within our own Galaxy had been found. However, one of these peculiar star-like objects, listed in the Third Cambridge Catalogue as 3C48,

displayed an astonishing and wholly unfamiliar spectrum. Not a single line coincided with the firmly established positions of known atomic spectral lines. Moreover, its optical radiation proved to be variable. This last circumstance clearly indicated that 3C48 must be small and compact — in short, of stellar type. This point perhaps requires explanation.

When we apply epithets such as “large” or “small, compact” to star-like objects, they must be understood on a stellar scale. “Large” would mean that light requires years to travel from one edge of the object to the other. But could such a giant wink in a coordinated fashion? Hardly. To imagine a mechanism capable of causing an object extending over many light-years to change its brightness simultaneously would mean abandoning the principle that the speed of light is the maximum possible speed; it would require the assumption of instantaneous transmission of signals. That would be far too obvious a step backward.

No, the only reasonable explanation lay in recognising the compact nature of these newly discovered celestial objects. But why did they shine so intensely?

Iosif Shklovsky suggested that what was being observed was the simultaneous outburst of several supernovae, accompanied by powerful radio emission. Geoffrey Burbidge advanced the hypothesis of a chain reaction of stellar explosions. William Fowler and Fred Hoyle, as the latter put it, “came to the idea of gathering all the stars together into a single super-body, exceeding the Sun in mass by millions

of times".

Yet it was difficult to venture such an assumption, since astronomers firmly believed that stars with masses greater than fifty solar masses could not exist. The super-star of Hoyle and Fowler would have had to shine more brightly than an entire galaxy. Meanwhile 3C48 appeared as a tiny spark, barely perceptible even in a large telescope.

An extremely interesting approach to the investigation of these "enigmatic" radio objects was chosen by Australian astronomers. At their disposal was a fine 70-metre parabolic radio telescope situated near Sydney. To increase its resolving power still further, they decided to use the Moon as a natural screen to occult radio sources. Since the position of the Moon at any given moment is known with precision, it is possible to determine equally precisely the moment when a source is screened and when it reappears. Naturally, for such work the highly sensitive receiver had to be carefully shielded from all possible local radio interference.

The Australian observers chose the source 3C273.[36] Here is how Fred Hoyle described the experiment:

> During the observations they took incredible precautions... Several tons of metal were removed from the telescope to make it possible to observe at lower elevations than the normal working range. A few hours before the moment when the source was to be occulted by the Moon, all local broadcasting stations repeatedly announced that no one was to switch on any radio transmitters during the observations.

[36] The name signifies that it was the 273rd object (ordered by right ascension) of the Third Cambridge Catalog of Radio Sources (3C), published in 1959. – DM

> All roads passing near the telescope were closed and patrolled to ensure that no cars were moving nearby. And, as a final touch, after the observations Cyril Hazard and John Bolton carried two duplicate recordings to Sydney on separate aeroplanes.

The complex experiment was crowned with success: 3C273 proved to be a double source, with two very small components separated by about 20 arcseconds. Such precise positional data enabled the American astronomer Maarten Schmidt, working at the Mount Wilson Observatory, to identify the radio source with a barely perceptible optical trace.

Did this mean that the radio waves were being emitted by a star?..

9.2 Quasars, or What Practice Does to Theory

After the identification of the enigmatic radio source with an optical star, it was necessary to obtain its spectrum.

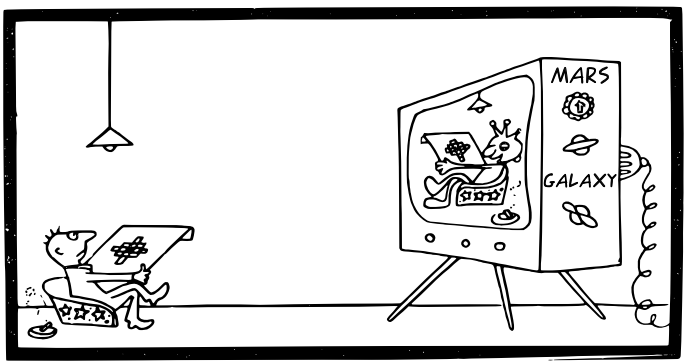
The acquisition of spectra from faint objects is an extraordinarily long and painstaking task. It demands patience, precision, and close attention from the investigator.

Maarten Schmidt was fortunate. Four of the six spectral lines unquestionably belonged either to hydrogen or to atoms of another element stripped of all their electrons.

Yet they were not in the positions where they ought to have been. As Schmidt supposed, they were shifted towards the red end of the spectrum by 16 per cent.

At once all four lines fell into place as hydrogen emission lines.

One might think that victory could now be celebrated. But matters were not so simple. If one assumes that the observed redshift has a cosmological origin, then the object 3C273 must lie at a distance of roughly two and a half billion light-years and be receding from us at about 45,000 kilometres per second. If, from such an unimaginable distance, it is still visible to us, then it cannot be an ordinary star at all. To shine across so vast a gulf, it would have to be brighter than an entire galaxy.



It is possible, of course, to suppose that the redshift of the spectrum is produced by the action of a powerful

gravitational field upon photons passing through it. In that case the mysterious object might be situated relatively near to us and represent a lump of dense, incandescent matter. However, the character of its spectrum is typical of a cloud of hot gas rather than of a dense solid body.

Astronomers hurried to the photographic archives. At major observatories thousands upon thousands of plates, obtained over many decades, are preserved in special storage rooms. It turned out that the strange object had been photographed many times. In the archives of the Harvard College Observatory "sky patrol" there were plates dating back to the end of the nineteenth century. On them the objects that had now attracted attention were already visible.

Until very recently, however, they had been regarded simply as faint stars belonging to our own Galaxy — stars whose only peculiarity, it was thought, consisted in their excessive emission of ultraviolet radiation. For that reason they had been called blue stars.

Using old negatives, observers established that the brightness of 3C273 had changed by about 50 per cent over a few years. This meant that the star-like object could not be very large. Otherwise it could not "wink" with such a short period. Therefore it was not a galaxy, not a cloud — it was... something entirely unknown. The observers began to call them quasi-stars — as if they were stars — and then combined the first and last syllables of the English term "quasi-stellar object". Thus arose the name that has since

become established: quasar.

After 3C273, other quasars were investigated. By now spectra have been obtained for more than a hundred of these remarkable objects, whose nature remains far from settled. Astronomers have even managed to obtain the spectrum of a very distant quasar whose emission lines are shifted by 288 per cent towards the red end of the spectrum. A shift of 288 per cent means that the observed wavelength is almost four times the true one. If the universe is described by the Friedmann model, the distance to such quasars must be of the order of eight billion light-years.

In 1965 the prominent astrophysicist Jesse Greenstein wrote:

> "As a concrete model (admittedly not explaining the variations in brightness) one may imagine a quasar as an excited gas cloud 600 light-years in diameter with a mass of 10^8 solar masses. At present it seems highly probable that the energy source of such a super-star may be gigantic explosions releasing either nuclear or gravitational energy."

The physicist William Corliss was surely right when he remarked:

> "From time to time Lady Nature creeps up on scientists and gives them a good kick... Since quasars appeared on the astronomical scene in the early 1960s, an expression of bewilderment has not left the faces of astronomers and cosmologists. No one knows what quasars are..."

Yet quasars did not confine themselves to the harmless role of a new variety of celestial object of unknown pedigree. They aspired to something more.

9.3 A Journey Along the *t*-Axis

The letter *t* is usually used to denote time. The sceptic may be inclined to smile: here, it might be said, the fantasies begin. Is it not only in bold works of science fiction that heroes travel to tomorrow and yesterday as though they were neighbouring tram stops?

Popular science writers also employ this device of temporal displacement. True, they must rely upon the goodwill and imagination of their readers. The usual signal of such an appeal is the phrase: "Let us imagine that..."

In astronomy, however, matters stand differently. It has already been said that an astronomer need only direct a telescope towards a celestial object situated, say, a thousand light-years from the Earth in order to see it as it was a thousand years ago. The light that brings us information today began its journey at the time when Sviatoslav I of Kiev ruled in Rus and waged war against Byzantium, two years before the birth of Al-Biruni, the great Khwarazmian encyclopaedist and the most renowned astronomer of the tenth century.

Now consider another object in the eyepiece. The redshift of its spectral lines indicates a distance of one million

light-years. We see it as it was in those remote times when our respected ancestors did not yet stand very firmly on two legs. The deeper we penetrate into space, the further we penetrate into time. Extragalactic astronomy has carried us beyond the hundred thousand light-years that roughly mark the diameter of our Galaxy and has introduced us to celestial bodies in the state in which nature formed them billions of years ago.

The discovery and study of quasar spectra have enabled astronomers to look still farther back along the axis of time — approximately eight billion years into the past. In the most recent years spectra have been obtained with such large redshifts that the received wavelengths are increased more than threefold.

In May 1965 Maarten Schmidt found that the quasar 3C9 possessed a redshift corresponding to a velocity equal to 80 per cent of the speed of light. That implies a distance of about nine billion light-years.

In 1967 a list was published containing 103 quasars. The largest spectral redshift was recorded for the quasar PKS 0237-23, discovered by Australian radio astronomers. Its recession velocity relative to the Earth was 247,000 kilometres per second, and the distance derived from Hubble's law, taking H = 100–75 km/s per megaparsec, amounted to 8–10 billion light-years.

But is it possible to approach still closer to the "beginning", to that mysterious and terrible moment when time and the radius of the universe — in the Friedmann model —

were at the zero point? Quasars are of no assistance here. There is reason to suspect that earlier than 8–10 billion years ago there were no stars, no galaxies, no quasars. One must seek some other source of still earlier information.

And then, in 1965 — a year rich in discoveries — a laboratory of Bell Telephone Laboratories was testing a highly sensitive radio telescope. One interference source after another was eliminated as the technicians adjusted the system. At last only a faint background noise remained, unchanged by direction or by time of operation.

It was assumed to be noise inherent in the apparatus. The radio telescope was dismantled, its internal components tested again and again. The engineers' professional pride had been touched, and the inspection proceeded to the last detail, to the last soldered joint. Everything seemed to have been corrected. The instrument was reassembled — and the noise returned.

After prolonged reflection, theorists concluded that the radiation could be nothing other than a constant background of cosmic radio emission, filling the universe with a uniform flux. Astrophysicists calculated that the noise corresponded to a temperature of approximately three degrees Kelvin and was detectable at various frequencies.[37]

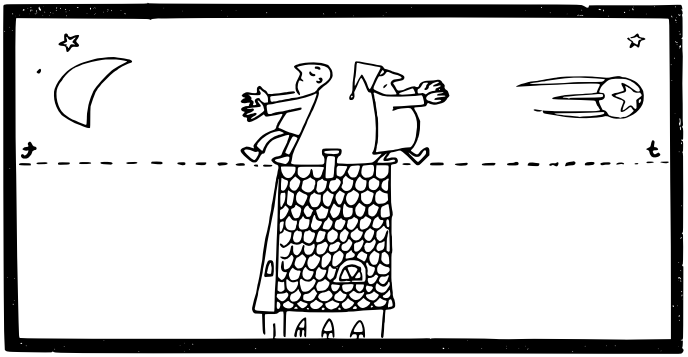
But from where could such a strange stream of energy in the universe arise?

Here the author invites the reader to recall the "hot" model of the universe proposed by George Gamow. About

[37] Discovered by Arno Penzias and Robert Wilson at Bell Telephone Laboratories this persistent background noise was later identified as the *cosmic microwave background radiation* (CMBR), Penzias and Wilson were awarded the Nobel Prize in Physics in 1978 for this work. – DM

300,000 years after the "beginning", dynamic equilibrium in the expanding fireball was disrupted. The density of the hot plasma fell to such an extent that radiation was able to separate from matter. Since then these homeless radio waves, wandering like the legendary Wandering Jew through the expanding universe, should have cooled precisely to 3–4 degrees Kelvin.

Was not the radiation discovered by the engineers at Bell Telephone Laboratories the very trace of those "relic waves" that broke away from the primordial inferno at the three-hundred-thousandth year of its boiling?



One may imagine the delight of the supporters of the hot model when this news arrived. "Relic radiation" — that was the name given to these aged and cooled quanta, a report on the state of the universe that has reached us after ten billion years. The discovery not only strengthened the position of the hot model. Relic radiation allowed as-

tronomers to descend from the time level of the quasars (8–10 billion years) to a level corresponding to 300,000 years after the beginning. At the same time it confirmed the idea that the universe once possessed a density a billion times greater than it does today.

Let us attempt to approach still closer to the zero point, remembering that appetite grows with eating. Once again we encounter the problem of an information carrier. Electromagnetic waves can carry us back only to 300,000 years after the origin. Before that they were bound to the turbulent plasma and were absorbed. And indeed, what could possibly survive in the violently boiling cauldron of the early universe?

Yet Academician Vitali Ginzburg, describing the journey towards the "beginning", names the next time step for the hot model as... one hundredth of a second after the explosion. At that moment the density of matter in the universe would have been only about one hundred times greater than the density of water, while the temperature would have reached roughly one billion degrees. Under such conditions, as we recall, protons combine with neutrons to form the nuclei of helium and other light elements.

Calculations show that in "hot" Alexander Friedmann models a considerable amount of helium should be produced: for every ninety hydrogen nuclei, about seven or eight helium nuclei and one nucleus of some other light element. Thus, if one could determine the abundance of helium in the universe, another "brick" would be laid in

the foundation of the hot model. At present the approximate helium content of the observable universe has been estimated at between 5 and 10 per cent. Physicists regard such a chemical composition as supporting the hot model.

Let us continue. No cosmologist, having learned the conditions at the hundredth second of the "creative work" of the Big Bang, would be satisfied. He would wish to know what the situation was at the tenth second and at the first. It might seem that possible carriers of information have been exhausted. Yet we have overlooked the most fashionable particles of the second half of the twentieth century: neutrinos and antineutrinos.

If it were possible to detect and count the neutrinos formed at the very beginning of the beginning, we could descend from the time level of one hundred seconds to about 0.3 seconds in the history of the hot model. Why precisely 0.3 seconds? Because at that moment the density of the exploding primeval matter would have been about ten million grams per cubic centimetre. This is approximately the density threshold for neutrinos. At higher densities these elusive particles — first postulated purely theoretically by Wolfgang Pauli and later described and named by Enrico Fermi — would be unable to pass through matter. But at lower densities they are scarcely absorbed at all and should have survived to our own epoch.

However, to capture "relic" neutrinos is a task that has not yet been accomplished. These particles interact with matter so weakly that they pass through planets and stars

as though through empty space, without reacting, without deflection, without scattering.

To detect relic neutrinos, it would be necessary to increase the sensitivity of present-day measurements by nearly a million times. This is an extraordinarily difficult undertaking. Indeed, it is so difficult that even the prospects for its solution remain highly uncertain.

Yet only three years ago the problem of registering neutrinos emitted by the Sun also seemed depressingly complex. Meanwhile, there is now little doubt that neutrino astronomy has a genuine future in the study of the Sun — and not a very distant future at that. In the "eyepiece" of a neutrino telescope we shall, in effect, observe the interior of our star. (A neutrino telescope can scarcely be called a telescope in the ordinary sense, so unlike is it in appearance to a traditional astronomical instrument. Yet if the name has been retained, why should one not refer to its counters as an "eyepiece"?)

If it proves possible to detect the "cold" relic neutrinos, this would constitute perhaps the most compelling evidence in favour of the hot model.

And finally, a last — though entirely legitimate — question. Suppose we learn to detect and record "cold" relic neutrinos and thus approach to within 0.3 s of the Big Bang. Can we come still closer? After 0.3 s the density of the primordial lump of matter exceeded, as we have said, 1×10^7 g/cm^3. Even neutrinos would be unable to escape from such a "dough". What, then, is to be done?

Here we arrive at the last real — though not yet practical — carrier of information: gravitational waves. They are the blue dream of the physics of tomorrow. True, from time to time reports appear describing experiments aimed at detecting gravitational radiation, yet these reports are not sufficiently convincing to inspire firm confidence.[38]

[38] This "dream" came true in 2015 when gravitational waves were detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) Scientific Collaboration, confirming a major prediction of Albert Einstein's general theory of relativity. The signal originated from the merger of two black holes. Key contributors Rainer Weiss, Kip Thorne, and Barry Barish were awarded the Nobel Prize in Physics in 2017 for this discovery. More on this in the last chapter. – DM

Gravitational waves ought to possess an even greater penetrating power than neutrinos and to reach us from regions whose density is expressed by 4×10^{93} g/cm^3.

At such densities we approach so closely to the longed-for zero point that the remaining fraction of time may be neglected.

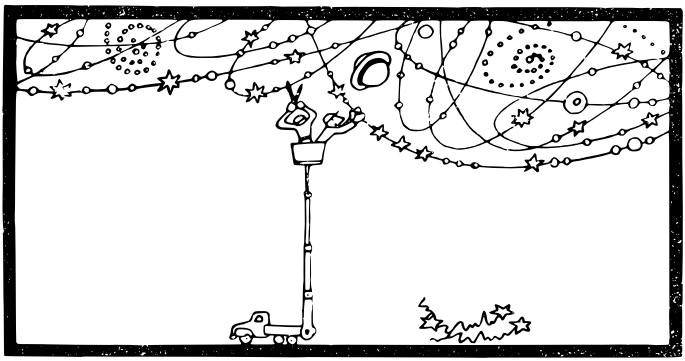
It has been suggested that at densities greater than 1×10^{93} g/cm^3 the laws of our physics cease to apply. The most fundamental principles — even, for example, the principle of causality — may break down.

Once, Gamow said that from a physical point of view we must completely forget about the existence of any period before the explosion and about the moment of the explosion itself. Although his "five acts" seemed to embrace the whole span of time from the zero point, Gamow believed that we could trace the development of the universe on the basis of reliable facts only from our own epoch back to one billion years after the "beginning". That was a quarter of a century ago. Then the "relic radiation" brought us one step closer — to 3×10^5 years after the beginning. It is not impossible that a few years may pass, and the earliest moment of the universe about which we possess reliable

facts will become 0.3 s. We shall live and see.

9.4 The Universe, the Year 1971

The criterion of truth for any theory is experiment. (The statement is so trivial that it is almost awkward to begin the concluding paragraph on the results of fifty-four years of classical general-relativistic cosmology with it.) For cosmology this is also a law. First, a science that was once entirely speculative has come to rest upon experimental data, upon observational data — a remarkable fact in itself. Secondly, does not the very phrase "classical general-relativistic cosmology" speak of its recognition? Today we may confidently say that all the facts at our disposal confirm the cosmology of the universe built upon the foundation of the general theory of relativity.



Of course, the models of the universe constructed on the basis of the Einstein–Friedman theory are only the first attempts at a mathematical description of the observed recession of the galaxies; the very first attempts, and certainly extremely simplified ones. We still know too little with certainty, we possess too few concrete facts about the universe, to construct an adequate model. But we are on the right path: facts, theory, and once again facts.

Naturally, cosmology has no shortage of difficulties. The first of them, as the outstanding Soviet cosmologist A.L. Zelmanov points out, lies in the multiplicity of models. For any value of the cosmological constant, Einstein's equations admit a multitude of solutions, and consequently a multitude of models of different types.

Recent works by the Soviet physicists Ya.B. Zeldovich and I.D. Novikov, as well as by R. Penrose and S. Hawking, insistently require recognition of the inevitability of the existence of "singular points" in cosmological solutions of the general-relativistic equations.

At the same time, the nature of the "singular point" (that is, the nature of the singular state of matter at the moment of maximum contraction) remains unknown. Some specialists regard it as a mathematical symbol of some physical state that is still unknown and inaccessible to analysis.

In 1969 the Soviet physicists V.A. Belinsky, E.M. Lifshitz and I.M. Khalatnikov, as well as the American C. Misner, considered the existence of singularity to be the result of the initial simplifications of the theory. In solving the equa-

tions of the general theory of relativity, they discovered a new class of cosmological models in which the universe, as it approaches the zero point, begins — because of its inhomogeneity — to oscillate in time. Thus the onset of a singular state is prevented.

In the works of the Soviet physicists the question of the physical meaning of time near the zero point is posed in a new way. Within a finite interval of time the number of oscillations proves to be infinite. Consequently, if time is measured by the number of cycles, it itself becomes infinite. In this sense the theory of a pulsating universe has its advantages. Some of its predictions have received astonishingly precise confirmation. Yet it also has serious difficulties, still not overcome either by observation or by theory.

Most likely the singularity indicates the limit up to which Einstein's theory of gravitation remains applicable. And beyond that?

At very high densities, evidently, another theory is required.

The single "beginning" of the universe also gives rise to a difficulty connected with the time scale. Recall that, according to the old scale of metagalactic distances which existed before 1952, the duration of the epoch of expansion was taken to be

$$T = \frac{1}{H} = \frac{1}{540} = 1.8 \times 10^9 \text{ years.}$$

This value was in glaring contradiction even with the age

of the Earth's crust. At present it is customary to assume

$$T = 1 \times 10^{10} \text{ years to } 1.3 \times 10^{10} \text{ years.}$$

This is, of course, better, but not by much. Cosmologists suppose that the age of the oldest stars is approximately 2.5×10^{10} years. Yet stars could not have formed before the "birth of the universe".

In general it must be said that many specialists in the field of cosmogony take a rather resolute attitude towards cosmology. For example, this is what Viktor Amazaspovich Ambartsumian, the founder and head of the world-renowned school of cosmogony, said:

> "...Some theoreticians, basing themselves on Hubble's law and on a number of very crude and arbitrary assumptions, have constructed hypothetical models of the universe which apparently reflect certain properties of the real universe. But the character of these models depends so strongly on the simplifying assumptions made that they should be regarded as very far removed from reality. As for me personally, I think that at the present stage of these theoretical works it does not even make sense to compare these models in detail with observations."

Academician V.A. Ambartsumian does not construct a theoretical model in advance which is only later subjected to empirical verification. His cosmogonic hypotheses, concerning the origin of stars and star clusters, galaxies and their interaction, arise as generalisations of observational results.

Extragalactic astronomy — the principal empirical foundation of cosmology — is still very young. The difficulties it encounters are truly formidable. Many observational results lie not only at the limit of the capabilities of unique instruments, but even beyond those limits. This circumstance allows different interpretations of certain empirical data. The reader will probably recall that all our reasoning has proceeded from the acceptance either of the perfect cosmological principle or of its limited version. The latter assumes that the universe is the same at different points and in different directions. The perfect cosmological principle further requires that this should be so at all times as well. However, at any stage of knowledge science always deals only with a limited part of the universe, and therefore conclusions about its homogeneity and isotropy inevitably remain hypothetical.

In recent years many cosmologists have begun to move away from the cosmological postulate, considering the requirements of homogeneity and isotropy of the universe too rigid, too greatly reducing the degree of reality of such a model. In turn, the rejection of the cosmological postulate immediately requires a revision of certain important conclusions. Thus, if one agrees that a closer description of the real space–time structure of the universe is provided by an anisotropic and inhomogeneous model, then the dependence of the finiteness or infiniteness of space on the sign of its curvature becomes ambiguous. However, disputes among specialists concerning an anisotropic and inhomogeneous universe are only intensifying. Many be-

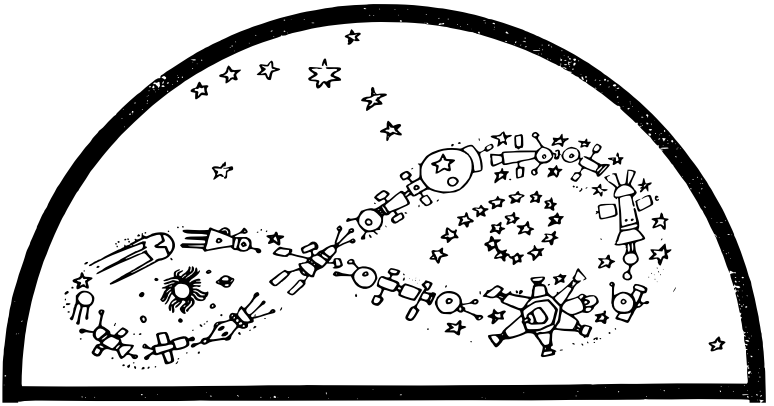
lieve that the universe may be inhomogeneous only "on a small scale"; on sufficiently large scales it is homogeneous.

Finally, one must also recall that the data of extragalactic astronomy are still insufficient to determine the average density of matter in the universe. This means that the question of the curvature of space also cannot be resolved. On the basis of empirical data we are not yet able to decide whether our world is closed or open.

Yes, there are many difficulties. Yet that only makes the science more interesting and more promising.

Academician Ginzburg offered a very striking comparison: "Cosmology and elementary particle physics are, as it were, two antipodes. And yet, as they say, opposites meet. Indeed, cosmology and elementary particle physics share one and the same feature that determines their significance in science. It is precisely in these fields — in astronomy and in physics respectively — that the boundary now runs between the region illuminated by knowledge, however incomplete, and the utter darkness of the unknown."

Well said, is it not?



10. The Battle for the Soul of the Cosmos

In which the reader becomes acquainted with competing hypotheses and at last stretches out his hands towards the question of how the universe arose — after which he understands that he may begin reading the book again from the start.

In the spring of 1958 Niels Bohr, discussing the questions of a unified theory of elementary particles proposed

by Werner Heisenberg and Wolfgang Pauli, incautiously remarked: "There is no doubt that we are dealing with a crazy theory. The question is whether it is crazy enough to be correct."

It cannot be said that the thought was entirely original. Let us unwind the tape of time backwards: Friedman, Einstein, Lobachevsky, Copernicus... these are all authors of completely mad ideas. One could extend the list further back through the centuries to the ancient principle of proof "by contradiction". The conclusion suggests itself: is it not natural that, as a result of the orderly course of development and the gradual accumulation of information, science finds itself faced with the necessity of a qualitative leap? Dialectics — that is truly a stainless weapon!

By the end of the 1950s the need for such a qualitative leap was being felt everywhere in science. It is no accident that in the same year, 1958 — only in the autumn, in October — at the First All-Union Conference on the Philosophical Questions of Natural Science, Corresponding Member of the Academy of Sciences of the USSR D.I. Blokhintsev expressed the same thought as Bohr: "A serious fundamental step forward is needed, and here perhaps only one word is required. The idea must be somehow completely 'mad'."

Unfortunately, in recent years Niels Bohr's remark has been quoted so many times in various kinds of literature that the criterion of "madness" has become almost the principal standard in evaluating certain ideas, at least at

the popular-science level. Yet there are "mad" ideas and "mad" ideas. The author, however, feels a strong desire to leave the reader a certain independence in judging them. He himself merely presents the information.

10.1 When an Idea Is Not Mad Enough

In 1948 the "short" scale of extragalactic distances was still in use, determined by means of the world value of Hubble's constant, taken to be 540 km/(s Mpc).

In 1948 the age of the observable universe was therefore estimated at only 2×10^9 years. Yet even the rocks on the surface of the Earth were considerably older. This conflict between theory and fact troubled specialists. Professor W. Bonnor related that "even Einstein, who never overestimated the importance of observations, was disturbed by this contradiction".

In 1948 observational results insistently suggested that our Galaxy was the largest stellar island in the entire observable world, and that its stars surpassed those of other galaxies in size and brightness. Such a conclusion nullified the perfect cosmological principle that lay at the foundation of relativistic cosmology.

Strictly speaking, the general theory of relativity did allow a way out of many of these difficulties, if one assumed the reality of the Λ-term and considered world models of the type proposed by Lemaître. But Einstein's own

prejudice against the cosmological constant so strongly influenced the psychology of researchers that one may state plainly: in 1948 there existed neither a single agreed opinion nor a single convincing model of the universe — rather, there were too many of the latter. The misfortune of each lay, first, in the fact that any given theory claimed uniqueness, rejecting all the rest. Secondly, each hypothesis brought with it new contradictions. And finally, none of them was sufficiently substantial to compete seriously with non-stationary (relativistic) cosmology.

In such an intellectual climate, in 1948, papers by English specialists appeared almost simultaneously. One was signed by Hermann Bondi, the youngest professor of mathematics at King's College London, and Thomas Gold — a man even younger in years and therefore still holding the post of lecturer at Trinity College, the famous Trinity College. The second paper was signed by the English astrophysicist, the thirty-three-year-old professor Fred Hoyle.

Both works proceeded from the postulation of the perfect cosmological principle.

Bondi and Gold constructed a phenomenological theory of the universe satisfying the perfect cosmological principle. In their model there was red shift — the universe expanded — yet there was no singularity, no "special (compressed) state", no "big bang", no disconcerting "beginning". How was this achieved?

The two authors rejected the "slippery" hypothesis of an initial super-dense state of matter and a creative explo-

sion, and assumed instead that "the world is eternal". The universe has always existed and has always expanded. The distinctive feature of the hypothesis was the assumption that matter is continuously created in space. Moreover, it is created in such quantity that this process completely compensates for the dilution caused by expansion. From the newly created material new galaxies are formed, and the average density of matter in the universe does not change.

The "birth of matter" proceeds very inconspicuously. In a volume corresponding to the famous building of the CMEA in Moscow, only a single atom of matter would be born in a year. And such an insignificant productivity, from our point of view, is entirely sufficient to maintain the density of matter in the universe at a constant level.

In the same year Fred Hoyle — no doubt known to the reader both as an astrophysicist and as the author of popular science-fiction novels — advanced a similar idea, giving the cosmological problem a new turn. Hoyle was always distinguished by boldness and originality of thought. His scientific activity has often been compared to a firework display — so many daring ideas and unexpected conceptions did he produce. The comparison is, however, a dangerous one: fireworks quickly fade. For the moment, let us return twenty-three years back and listen to Hoyle and his new hypothesis.

In order to rid himself of the melancholy picture of an ever "thinning" world, Hoyle also proposed a model of a "steady state of the expanding universe". He merely modi-

fied Einstein's equations slightly and derived the Bondi–Gold model as a consequence of the new field equations. To explain the origin of galaxies, Hoyle assumed that hydrogen is created in space, and even introduced the concept of a certain "creative field", brushing aside the fact that such processes were unknown to physicists.

"...Where does matter come from? From nowhere! Matter is content simply to appear ready-made..."

In earlier theories it was assumed that at a certain moment the entire quantity of matter in the universe came into being, and the whole process of creation was imagined as a gigantic explosion. As for me, I find this idea far stranger than the idea of continuous creation," Hoyle wrote in 1952.

And despite the clearly subjective character of the hypothesis, it appeared attractive and elegant to many astronomers. "The disagreement between the age of the Earth and that of the universe disappears — the world is eternal!" The unpleasant notion of a creative explosion was also removed, an event which, by virtue of its uniqueness, defied explanation.

> "I find the very idea repugnant that 'initial conditions' are required to explain the most general features of our existence. That would mean that the universe is a rather paltry affair, capable only of rattling like a huge factory — and even then only after a long period of adjustment, like the old motor-car I drove in the first post-war years. In cosmological research I adhere to the view that all the important features

> of the universe are already contained in its laws, and are not introduced from outside."

In these words of F. Hoyle, spoken in 1963, a fairly definite creed is expressed. Remember this date — 1963. We shall need it again. Meanwhile, beginning in 1948, Hoyle's hypothesis steadily gained supporters and acquired ever more detail. "Who knows, perhaps somewhere in the unexplored depths of galaxies there is concealed a mechanism that produces 'something from nothing,'" thought the hesitant and cautious, not daring openly to oppose the forceful Englishmen.

Professor R. Lyttleton, a Fellow of the Royal Society of London and of the Royal Astronomical Society, even devised an impressive analogy for this process, speculating on the fact that we live in a four-dimensional world. As is usual in such cases, the analogy is based on reducing the number of dimensions in order to increase clarity.

Imagine, then, a bucket filled with water. The surface of the water is our flat world, upon which lies, spread out, the familiar inhabitant — the flat creature. Now suppose that rain begins to fall. The drops strike the surface of our flat world, creating for the flat creature the impression of the "birth of matter", for the concept of "rain" from a third dimension is inaccessible to it. The raindrops fill the bucket and overflow its rim, analogous to galaxies passing beyond the horizon of events in our world. And so everything seems to be in place: the "birth of matter", the "expansion of the universe", and its "steady state".

There was, of course, a small difficulty in this explanation as well. Why, after all, does the universe expand? In 1959 R. Lyttleton and H. Bondi attempted to answer this question in detail by proposing a model of an "Electric Universe". Both specialists suggested that the expansion of the universe could be explained by electrical repulsion. For this it was sufficient to assume an exceedingly slight inequality between positive and negative charges:

$$\frac{e^+ - |e^-|}{|e^-|} = 2 \times 10^{-18}.$$

Lyttleton was even confident that this hypothesis would not be difficult to test under laboratory conditions. In 1961–1963 V. Hughes and his collaborators succeeded in showing that no such inequality of charges is observed, even with a precision two orders of magnitude greater than that predicted, namely

$$\frac{e^+ - |e^-|}{|e^-|} = 10^{-20}.$$

After that the hypothesis of electrical repulsion lost all attractiveness in the eyes of researchers; indeed, its authors themselves now appear to regard it with considerable scepticism.

Time passes. Science advances. Gradually certain theoretical inconsistencies also began to appear. For example, the mathematical equivalent of the universe of Bondi, Gold, and Hoyle is the empty mathematical model of de Sitter, which we have already mentioned. For the de Sitter model

the Hubble law is exact, at all distances. Observations, however, do not confirm this.

Although the hypothesis of the steady-state universe enjoyed popularity, many Soviet and foreign physicists and astronomers refused to accept it. Yet such questions are not decided by voting, nor even by authoritative theoretical argument. For example, when in September 1952 Walter Baade spoke in Rome at the Congress of the International Astronomical Union and declared the need to revise the scale of extragalactic distances and to increase the age of the universe, this in itself reduced the urgency and relevance of the steady-state hypothesis. However, the time for open and unequivocal criticism had not yet come. The prerogative of passing judgement on any theory belongs to experiment.

It is true that in that same year there appeared one outspoken opponent of the theory of Bondi, Gold, and Hoyle — the Pope. Yes, the same indefatigable Pius XII declared from the height of the apostolic throne that the theory of the steady-state universe was unacceptable, since it did not accord with divine revelation. According to the Bible, the world "was created". In this respect the "big bang" suited the Pope far better. Yet the objections of the Catholic pontiff seem to have stirred few people. Far more important was the question of experiment.

Could observation confirm or refute the steady-state cosmology? Yes, it could. In the model of Hoyle, Bondi, and Gold the average density of matter remains constant

in time. In expanding models, by contrast, the density in the past must have been significantly greater than it is now.

In the steady-state model the universe, separated from the present by billions of years, would in no way differ from the modern one. Relativistic cosmology, however, envisaged a definite evolution of the universe in time.

What experiment, then, could be performed? To measure precisely the average density of matter in the universe is beyond the power of present-day science. To count how the number of galaxies changes with increasing distance is likewise hopeless for now, since it is extremely difficult to measure with sufficient accuracy the distances to the most remote stellar systems. If only all galaxies were alike — but their properties differ enormously. Their luminosities also differ, and luminosity is one of the principal criteria for determining distance.[39]

[39] See the next chapter for updates in this regard. – DM

And then came 1963 — the year when, as J. Greenstein writes, "astronomers discovered that five celestial objects, which had been regarded as faint stars of our Galaxy, though somewhat unusual ones, are in fact perhaps the most astonishing and mysterious objects ever observed by man." In 1963 quasars were discovered.

Of course, the mere fact of this discovery did not in itself prove anything, although it was precisely these remarkable objects of the stellar world that destroyed the steady-state theory. As you will recall, they all possess substantial red shifts. That is to say, we see these "monsters of the stellar world" now as they — and therefore the universe — were

3×10^9, 5×10^9, 7×10^9, and even 9×10^9 years ago. In the space–time remoteness of the old universe such strange objects are numerous. In our immediate neighbourhood, however — even out to 1×10^9 light-years — there is not a single one.

Thus the observations of recent years — the discovery of quasars and especially of the "relic radiation" — finally dealt a fatal blow to the steady-state hypothesis of Bondi and Gold. It has been suggested that if the "relic radiation" had been discovered twenty years earlier, such a hypothesis would never have arisen. At the present level of knowledge one may regard as established the hypothesis of expansion and of the evolution of the universe in time.

This was understood both by the authors and by the defenders of the steady-state hypothesis. Fred Hoyle himself, concluding in his lectures the section devoted to quasars, was compelled to admit:

> "Perhaps we have at last obtained the key to the connection between cosmology and astronomy. Quasars look as our universe is supposed, according to certain cosmological theories, to have looked at its origin. Over the past ten years (1955–1965) there have existed the so-called 'big bang' theory, according to which the entire universe originated at one and the same time, and the 'steady-state theory', according to which the formation of nucleons proceeds quietly all the time. Perhaps the truth lies somewhere in between. Perhaps the existence of quasars indicates that instead of one great explosion there occur many small ones in the universe. Nevertheless, these small

> explosions are far more powerful than the quiet processes of the steady-state theory."

With these words the author of the steady-state hypothesis renounced his own creation. That requires no small measure of courage. More often people, having discovered their error, are unable to admit their mistakes.

Today the recession of galaxies and quasars may, perhaps, be regarded as established. One may also acknowledge that the model of an expanding universe most accurately corresponds to the present level of knowledge. As for the steady-state hypothesis, it proved to be not nearly mad enough.

10.2 Kabbalistics of the Twentieth Century

Once, very long ago — perhaps at the very beginning of our era — alongside the three most important "sciences", magic, astrology, and alchemy, there was held in great esteem a mystical religious philosophy set out in Jewish Kabbalistic writings. The followers of the Kabbalah — which in ancient Hebrew simply meant "tradition" — engaged in symbolic interpretation of sacred texts, assigning special mystical significance to words and numbers.

But allow me, the indignant reader will say, what have some elderly Kabbalists to do with the twentieth century?..

Here is what. Open the second volume of the *Physical Encyclopaedic Dictionary* to page 496. In the article "Cos-

mology", written by A.L. Zelmanov, in the section entitled

> "Principal difficulties that played an explicit or implicit role in the emergence of new theories...", under number 2 one reads: "...2. An unexplained empirical connection between intergalactic parameters and microphysical constants."

What does this mean?

In the 1930s, Arthur Eddington, brimming with the ideas of relativity, conceived — for purposes of popularisation — the plan of calculating... the number of elementary particles in the universe.

"What sort of problem is that?" numerous philosophers of physics and physicists of philosophy exclaimed in astonishment. "How can one count the infinite in the immeasurable?.."

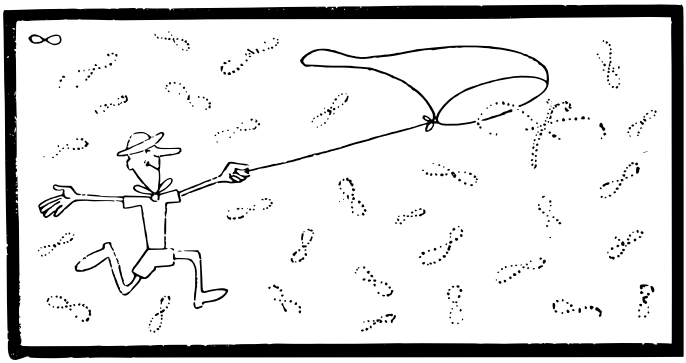
However, according to the theory of relativity, one could imagine the universe as closed and calculate its diameter and volume. The diameter turned out to be approximately (1×10^{28} cm), and the volume about (1×10^{84} cm^3). The mean density of matter was also known to Eddington; by the estimates of that time it was roughly (1×10^{-28} g/cm^3).

If one now multiplies the volume by the density, the mass of matter in the universe comes to something of the order of (1×10^{56} g). The mass of a single nucleon is approximately (1×10^{-24} g). The number of particles in the

universe is then found by a simple division:

$$\frac{1 \times 10^{56}}{1 \times 10^{-24}} = 1 \times 10^{80}.$$

This is an enormous number.



But why did it so impress Arthur Stanley Eddington that in his work *Fundamental Theory* he devoted almost a central place to mathematical manipulations with large dimensionless coefficients — the so-called world constants?

Let us step slightly further back in time, to the 1920s. At the University of Bristol a lanky student named Paul Dirac was grappling with the problem of obtaining a higher technical education. In only a few years the world would know his full name — Paul Adrien Maurice Dirac — though such formal usage is hardly customary in England. For the moment he was simply Paul — a young man with a cast of mind ill suited to engineering practice.

One day his fellow students showed him a competition problem that had been set at University of Cambridge during some annual student conference or Olympiad. The conditions were as follows:

> "Three fishermen went out to catch fish. A stormy night forced them to seek shelter in a lonely hut. To wait out the bad weather, the fishermen fell asleep. However, one of them could not sleep. Looking outside and seeing that the storm was subsiding, he decided to take his share of the catch and go home without disturbing his companions. When dividing the fish, one fish remained over. So that no one should feel slighted, the first fisherman threw it back into the sea."
>
> "Soon after his departure, the second fisherman awoke. Not knowing that the division had already taken place, he again arranged the catch into three parts, obtained one extra fish, threw it into the sea, took his share, and went home."
>
> "With the third fisherman the whole story was repeated. He too divided the catch into three parts, threw the surplus fish into the sea, took his share, and departed."
>
> The question was: what was the smallest number of fish that satisfied these conditions?

The author first heard this Cambridge problem while still a student, at a physics seminar conducted by the excellent lecturer S.B. Vrassky. As far as memory serves, we spent quite a long time solving it together. However, the answer attributed to Paul Dirac astonished us all.

Dirac presented the solution with the answer: "minus two fish"! What concern is it of mathematics whether the fish are positive or negative?

After graduating from the University of Bristol, P. A. M. Dirac specialised in theoretical physics at the University of Cambridge. In 1928 he worked under Ernest Rutherford, constructing a relativistic theory of the motion of the electron. He addressed many fundamental questions of theoretical physics.

What interests us here, however, are Dirac's works that connected Eddington's calculations with the unexpected idea that the world constants might not be constant. Long before, Henri Poincaré had expressed the idea that fundamental constants might vary. Yet in order to speak of anything definite, constants — or so it would seem — are necessary.

Having acquainted himself with Eddington's calculations, Paul Dirac in 1937 decided to introduce as a unit of time one of the quantities characterising the world at its elementary level — the time of so-called strong interactions, 10^{-23} s. Roughly speaking, this is the time required for an elementary particle, travelling at the speed of light, to move a distance equal to its own diameter.

If one calculates, in these new units, the lifetime of the universe (we mean the expanding universe, T = 13 billion years), one obtains 10^{40}. An interesting value! The ratio of the diameter of the universe (10^{28} cm) to the size of a nucleon (10^{-13} cm) is also approximately 10^{40}. The ratio of

the square of the nucleon diameter to the square of the "Planck quantum of space" L^2 (where $L^2 = G \cdot h/c^3$ and h is the Planck constant) again yields 10^{40}.

But the most striking point is that the number of elementary particles in the universe (10^{80}) is equal to the square of the dimensionless lifetime of the universe itself: $(10^{40})^2$. Can one suppose that such a relation is merely an accident peculiar to our epoch? Hardly. It seems more plausible to assume that this relation, $(10^{40})^2$ between time and the number of particles, has always held. And since the lifetime of the universe continuously increases, the number of particles must also increase.

Thus, by juggling intergalactic parameters and microphysical constants, we arrive at the necessity for the number of particles to grow with time. Yet this was still not all. Dirac took the ratio of the forces of strong interaction to the forces of gravitation and again obtained 10^{40}. Does this mean that these quantities are connected with one another? But the lifetime of the universe, from the "beginning" to the present day — whether dimensional or dimensionless — increases. Does this not imply that the gravitational constant must decrease?

Paul Dirac himself, having put forward the idea, soon cooled towards it. The war with Germany and other concerns diverted his attention from the question whether the world constants might be functions of the age of the universe. Others took up his ideas. Thus the thesis of the "ageing of gravitation" gave rise to a veritable cascade of

works developing the suggestions expressed by the English physicist.

In 1944 the German theoretical physicist Pascual Jordan attempted to implement Dirac's ideas. He proposed a spherical model of the universe expanding linearly with time. In "Jordan's world" matter was continuously created, and the "constant" of gravitation varied inversely with the age of the universe.

This theory was one of the many generalisations of Albert Einstein's theory. And, as the reader sees, each such generalisation may be associated with its own cosmology.

With the passage of time, cosmology based on the theory of relativity found itself confronted with an ever-increasing number of competing hypotheses. If the period before the beginning of the Second World War is regarded by specialists as a time of "development of theoretical conceptions and accumulation of empirical material concerning the most distant nebulae", then after the war there came a period of generalisation of these results and preparation of new theories.

Mathematical models of the universe are studied by many outstanding specialists both in our country and abroad. Some solutions, even those unsuitable for describing reality, nevertheless provide powerful impulses to the development of pure theory.

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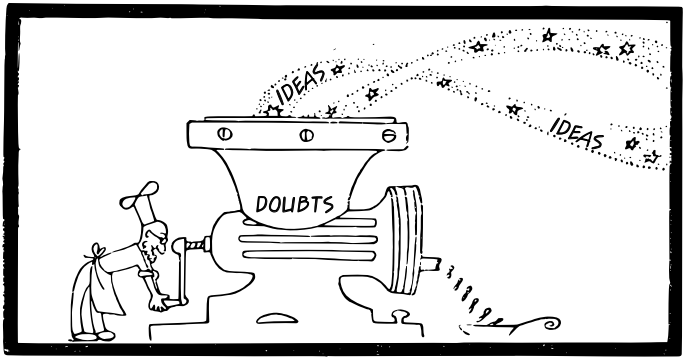

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The question arises: may one regard numerical manipulation of coefficients as mere speculation? "10^{40}" is the fashionable number of the twentieth century. But does it express any genuine regularity, or does it have roughly the same meaning as the number ten in the doctrine of the Pythagoreans? At present it is difficult to say. The analysis has not yet been carried through to the end. Both polar views have their authoritative supporters and their equally authoritative opponents. So one must wait.

Today the group of scientists attempting to realise Paul Dirac's ideas is headed by Robert H. Dicke, a young and exceptionally active professor at Princeton University. It was he who proposed the interpretation of an unexplained background noise as relic radiation. He also carried out an excellent experiment testing the equality of inertial and

gravitational mass, increasing the accuracy of previous results by three orders of magnitude.

Together with his graduate student Carl H. Brans, Dicke proposed a new theory of the development of the universe — the Brans–Dicke theory. His model did not require "Jordan's creative field", and the gravitational constant in it varied proportionally with time, rather than inversely as in earlier theories. In general, the theory made a very favourable impression — until it came to calculations.

According to the Brans–Dicke theory, the perihelion of Mercury's orbit would rotate, exceeding the classical prediction by 39 arcseconds per century, instead of the 43 arcseconds given by Albert Einstein's theory. To remove the discrepancy, Dicke assumed that the Sun is slightly flattened, and that this oblateness contributes the missing 4 arcseconds per century. Moreover, Dicke performed an experiment and announced that the oblateness of our star had been demonstrated. Yet a scientific experiment is usually understood to be something that can be repeated by others under similar conditions.

Dicke's observational result has not yet been confirmed by anyone. Nevertheless, his theory, based on a realisation of Dirac's ideas, is today regarded by many as the principal competitor to general relativity. Whether this judgement is justified or mistaken — time will show.

10.3 Matter + Antimatter = ?

At the Royal Institute of Technology in Stockholm, the Department of Plasma Physics was headed by Professor Hannes Alfvén, described by Academician B.P. Konstantinov as one of the most interesting and original physicists and astrophysicists of our time. His work in magnetohydrodynamics — a young yet rapidly developing branch of modern physics — is difficult to overestimate. In recognition of his scientific achievements, Alfvén was elected a foreign member of the USSR Academy of Sciences in 1966.

Physicists are familiar with many of Alfvén's profound investigations. Recently, however, a popular book[40] by the Swedish professor was published, devoted to a cosmological hypothesis which he had long been developing together with Professor Oskar Klein. The essence of their hypothesis is as follows: taking as a foundation the concept of complete charge symmetry of the world, the authors arrive at the conclusion that matter and antimatter exist in the universe on equal terms. Upon this basis they construct a hypothesis of the origin of the universe.

[40] The popular science book being referred to is *Worlds–Antiworlds* by Alfvén which presents in a popular form, ideas related to the cosmological hypothesis he developed together with Klein. – DM

Professor Alfvén formulated his aims in these words:

> "In our analysis we tried not to resort to any new laws of nature; on the contrary, we attempted to see how far one can proceed on the basis of already known laws. In other words, we tried to incorporate the problems of cosmology into the system of ideas of laboratory physics. We also avoided posing the questions: how did the universe arise, and how far

> away are its boundaries, if such boundaries exist at all? We modestly confined ourselves to examining the last trillion years in time and the nearest trillion light-years in space."

Alfvén and Klein begin their consideration of the universe at a stage when an large spherical region, filled with highly rarefied primordial plasma containing equal numbers of protons and antiprotons, slowly contracts under the laws of gravitation. At a certain stage of contraction, the density of the plasma becomes high enough for annihilation processes to become significant, producing radiation.

This radiation — chiefly in the form of gamma rays and radio waves — accumulates, and its pressure increases until it halts the contraction. Then a radiation explosion occurs. The compressed plasma passes into a state of expansion, which continues to this day, as is eloquently indicated by the galactic redshift.

But where, then, are the galaxies, the stars, the planets? Is everything everywhere merely plasma — and plasma composed in equal parts of particles and antiparticles?

The authors of the hypothesis maintain that galaxies must form simultaneously with the expansion, that is, from the very moment of the explosion events proceed in a manner not greatly different from the model proposed by George Gamow. The only complication is antimatter.

How many starships have set off from the pages of science-fiction novels toward distant stellar systems, carrying on board "full tanks of matter" and equally full tanks

of antimatter? "Meeting at the focus of a gigantic mirror, matter and antimatter annihilate, accelerating the starship to velocities close to that of light."

Now for some anti-fantasy.

Have you ever sprinkled water on a red-hot stove? Almost certainly. And what happened? Nothing remarkable? Next time, observe more carefully.

> "If one drops a small quantity of water on a plate heated to slightly above 100 °C, the drop almost instantly evaporates with a hiss," writes Hannes Alfvén in his book *Worlds-Antiworlds*. "If the temperature is increased a little further, the drop seems to explode and disappears within fractions of a second. But if the plate is heated to several hundred degrees, until it glows red, a different phenomenon occurs. The drop does not evaporate instantly; it may remain on the hot surface for more than five minutes. It begins to tremble and dart about from side to side, gradually decreasing in size before finally vanishing."

The explanation is simple: between the red-hot plate and the drop there forms a layer of vapour which acts as thermal insulation. The higher the temperature of the plate, the thicker the vapour layer — the better the insulation, and the longer the drop survives. Simple — yet it appears paradoxical.

This phenomenon was investigated and described as early as the nineteenth century and received the name of the *Leidenfrost effect*, after its discoverer.

Now let us return to the starship propelled by annihilation. Lumps of matter and antimatter, hurled out by magnetic guns, meet at the focus of a reflector. An explosion? A blinding flash brighter than a solar prominence?

One should hesitate. If a layer of vapour can insulate a drop of water from red-hot metal, might not an analogous effect occur here? When matter and antimatter begin to annihilate, the intense radiation produced would generate pressure. Could this radiation form a kind of barrier, partially separating the reacting substances and regulating the rate of annihilation?

The simple picture of instantaneous, total destruction may be misleading. Nature has a habit of complicating what imagination renders too easily spectacular.

Nothing of the kind. Do not shut your eyes, and there is no need to cover yourself with a white sheet. A flash? There is one, but it is small — like a tram spark. And then? Then, silently (the phenomenon occurs in the silent depths of a vacuum), the two pieces fly apart in opposite directions. An effect analogous to the Leidenfrost effect.

At the first contact of matter and antimatter, annihilation occurs, and the forces of the incipient explosion scatter the pieces away from one another. Of course, comparing the beginning of annihilation with a spark on a tram arc may seem rather improper — and, above all, disappointing for writers of fiction — yet there exists the supposition that the annihilation reaction should proceed quite slowly: the "interaction cross-section", as specialists say, is insuffi-

cient for the reaction to occur with high intensity.

Now let us return to the universe. At the initial moment of expansion, after the radiation explosion, the plasma is hot. Hot plasma possesses excellent electrical conductivity. In the expanding universe magnetic fields are generated and rage. It is these fields that play the role of a separator, separating positively charged protons from negatively charged antiprotons; they prevent all the substance from burning up, from completely annihilating.

Subsequently, plasma composed of particles will form matter; from it galaxies, stars, and planets will condense, and man will appear. From antiparticles everything will proceed in the same way, only with the corresponding prefix "anti".

Alfvén and Klein consider that even within our Galaxy there may exist stars of matter and of antimatter. You may ask: what if they approach one another? Well then. Long before close contact, the annihilation reaction would raise the radiation pressure in the boundary layer (the "Leidenfrost layer") to such an extent that bodies of matter and antimatter would immediately begin to move apart. Alfvén writes that the "Leidenfrost layer" may be extremely thin on cosmic scales. Under certain conditions its thickness remains within 0.001 light years and even less. Such a thickness is apparently sufficient for effective separation of co-matter and antimatter. (By "co-matter" the Swedish physicist means the ordinary matter of our world.)

It is interesting to note that it is extraordinarily difficult

to distinguish a star from an anti-star. In principle, the electromagnetic radiation of both would be identical. It would be another matter if one could learn to register neutrinos and antineutrinos from distant luminaries. Yet the fate of "neutrino astronomy" remains highly uncertain.

Academician B.P. Konstantinov states that the views of Hannes Alfvén and Oskar Klein on the equal status of matter and antimatter in the universe are not shared by the majority of physicists and astronomers. "I would even say that this hypothesis provokes in physicists, to some extent, a feeling of aversion." The reason lies in the absence of evidence for the existence of antimatter in the universe, as well as in observed symmetry violations in the interaction of elementary particles and in beta decay.

> "According to the data presently available, it is entirely possible that the universe consists only of protons and electrons, together with four types of neutrino, and also quanta of electromagnetic radiation. Yet this position, like the hypothesis of Alfvén and Klein, cannot be regarded as proven. It is precisely for this reason that Alfvén's book is of great interest."

Thus concludes the afterword to *Worlds-Antiworlds*, which presents yet another intriguing hypothesis concerning the development of the universe.

One may describe many curious hypotheses. One could speak of the idea of Professor Konstantin Stanyukovich, according to which the world arose from the collision of two elementary particles. Or one might outline the hypothesis

of John Archibald Wheeler and Charles Misner, according to which electric charges are manifestations of special properties of space itself; or the hypothesis of Richard Feynman concerning the so-called "neutrino universe".

Many — very many — interesting and highly ingenious ideas have been expressed regarding the origin and development of the universe. In each of them, undoubtedly, there lies some rational kernel. After all, such ideas are proposed by people of great knowledge. They themselves strive, above all, to ensure that nothing in their suppositions contradicts established laws. A new theory, however "mad" it may appear, has no right to deny the old laws confirmed by experiment. It may only generalise them; it may rise above them. Without observing this condition, no one would even consider "new" ideas.

The days of the Greeks in their long chitons are gone beyond recall. It was they — sages and philosophers — who constructed their hypothetical systems while strolling along paths and reasoning. Merely reasoning. Today that is not enough. "Those who do not know mathematics find it difficult to grasp the real, deep beauty of nature..." says Richard Feynman in his lectures on the relation between mathematics and physics. "She (nature) provides information in only one form, and we have no right to demand that she change her language in order to attract our attention..."

Complex and subtle mathematical constructions, the developing theory of gravitation, the theory of elementary particles, quantum theory — this is far from a complete list

of the scientific arsenal of modern cosmology. Humanity has already accumulated a considerable store of knowledge, and it is not impossible that the present generation may yet witness a powerful qualitative leap, analogous to the revolution accomplished by Albert Einstein, though at another — and, one would hope, higher — theoretical level.

10.4 The Battle of Ideas Continues

"If one abandons the principle of contradiction, then all judgements will stand on the same level of credibility, and it will be impossible to distinguish true judgements from false ones," writes the philosopher Barrows Dunham in his book *Man Against Myth*. Contradictions, at any rate, are abundant in cosmology. Perhaps in no other science can one find so many competing hypotheses and so many misunderstandings. At one time, among a certain group of scholars, there was even discussion as to whether cosmology could be regarded as a science at all.

Doubts were intensified by the fact that the observations of extragalactic astronomy — which provide the principal empirical material for cosmology — lie, at best, on the very edge of the capabilities of astronomical technique. More often they extend beyond those limits. In such cases, the results of experiment acquire a functional dependence upon the imagination of the experimenter, allowing the broadest possible interpretation.

In practice, during the first half of the present century, almost any cosmological scheme could be reconciled with observational data by slightly "adjusting" the results. If certain data contradicted a chosen model, they could, without consequence, be declared inaccurate or even simply incorrect. In such circumstances, the ranks of cosmologists were joined by many theoreticians, each cherishing and cultivating his own hypothesis, his own model.

Classical physics, up to the beginning of the twentieth century, adhered — following the "light hand" of Francis Bacon and Isaac Newton — largely to what was termed the "naively realist conception" of scientific notions. (This is how the view is described by prominent Soviet philosophers, corresponding member of the Academy of Sciences of the USSR Pavel Kopnin and Professor Pyotr Dyshlevy.) According to this conception, any notion was regarded as a "direct and immediate reflection of some element of objective reality". However, as new facts accumulated, and as the need arose for concepts lacking visual intuitiveness, physicists were compelled increasingly to depart from this conception.

It was in such an "unstable" period that the general theory of relativity appeared. Although its essence was rooted in vast layers of experimental results and earlier theories, outwardly it seemed more a priori than even such a summit of ancient abstract thought as Euclidean geometry. This apparent apriorism gave rise to two irreconcilable camps within science.

Among one group of theoretical physicists there emerged the idea of a complete "reconstruction of physics on an axiomatic basis". This meant a rejection of experience and the derivation of all physical laws from a few axioms. The English scientists Arthur Eddington and Edward Arthur Milne were particularly ardent advocates of this approach. Proceeding from Immanuel Kant's idea that true science begins when reason dictates laws to nature rather than borrowing them from it, Eddington wrote:

> "In the whole system of the laws of physics there is nothing that could not be unambiguously deduced logically from considerations of the theory of knowledge."

The English astrophysicist Milne did not confine himself, like Eddington, to proclaiming the doctrine of the apriority of knowledge. He made a serious attempt to construct a coherent theoretical system founded solely upon the cosmological principle. From this system, in his view, one could logically derive — without recourse to experiment — the entire foundation of geometry and physics. This position met with sharp criticism from many prominent figures in science. "I consider that these ideas represent a serious danger to the healthy development of science," wrote Max Born, who devoted a lecture to the philosophy of Eddington and Milne, delivered at a joint meeting of the Durham Philosophical Society and the Society of Pure Science at King's College in Newcastle upon Tyne on 21 May 1943. Neither Eddington nor Milne succeeded in finding new fruitful ideas for their system of views, and both remained captive to the ancient conception of the apriority

of knowledge.

There were, however, other representatives of science who, accusing the former of neo-Aristotelianism, rushed to the opposite extreme. They demanded that all scientific principles, without exception, be derived solely from experience — from particular experimental results to generalisation. Any theoretical conclusion, whether particular or general, was, in the opinion of these "false Galileans" (as philosophers labelled them), to follow directly and immediately from experiment.

Such swings from one extreme to another, the emergence of numerous contradictory theories, hypotheses and models, and the absence of reliable experimental data led to what was described as "the greatest confusion and turmoil in the minds of astronomers". Many concepts required clarification. Above all, it was necessary to distinguish the proper spheres of natural science and philosophy, to learn to make philosophical generalisations on the basis of experimental and theoretical data, rather than to force the results of experience into a ready-made philosophical scheme.

Natural science cannot exist without philosophy, which generalises its conclusions and prepares the ground for the next advance into the unknown. Yet philosophy is too powerful an instrument to be used carelessly or lightly.

One should not forget the thought expressed by Vladimir Lenin on the genuinely philosophical formulation of a problem: "The question is not whether there is motion,

but how to express it in the logic of concepts."

An example of a correct and judicious approach to philosophical generalisation of the achievements of natural science may be seen in the path indicated by Lenin. A question often arises: how could Lenin, who did not consider himself a specialist in the natural sciences, arrive not only at such fruitful anticipations as, for example, the inexhaustibility of the electron, but also at conclusions of fundamental importance for the development of science as a whole?

The answer lies in Lenin's own words:

> "It goes without saying that, in examining the question of the connection between one school of the latest physicists and the revival of philosophical idealism, we are far from wishing to touch upon the special doctrines of physics. We are interested exclusively in the epistemological conclusions drawn from certain definite propositions and well-known discoveries. These epistemological conclusions are so self-evident that many physicists already touch upon them. Moreover, among physicists there already exist different tendencies, definite schools taking shape on this basis. Our task, therefore, is limited to presenting clearly the essence of the divergence between these tendencies and their relation to the fundamental lines of philosophy."

It is undoubtedly correct to maintain that the natural sciences cannot develop in isolation from philosophy, which generalises their conclusions and assists in forming hy-

potheses. Yet it is no less correct that philosophy itself, without the vitalising influence of the natural sciences, becomes a lifeless scheme.

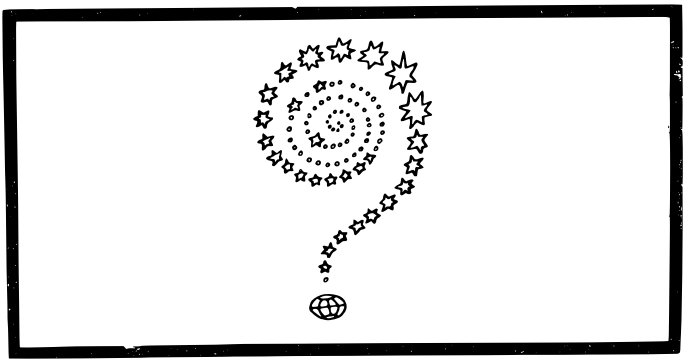
10.5 What Is the Universe?

Among philosophers there exist different views as to what should be understood by the universe. One group maintains that the physical laws discovered for the world around us may be extended to "all matter in general". Thus, for example, the Saratov professor Yakov Askin holds that, so long as there is no proof that a given physical law is confined within definite limits, it may (and indeed should) be extended to the whole material world. By analogy with jurisprudence, Askin even formulates a certain principle of the "presumption of extrapolability".

One need not be alarmed by the complexity of the terminology. In legal usage, a "presumption" signifies the recognition of a fact as valid until the contrary is proven. The term "extrapolation" may quite calmly be replaced by the word "extension", since it denotes the extension of concepts and laws relating to one definite domain to another. The principle of extending laws derived for a limited region of the universe to the world as a whole is introduced by analogy with the legal principle of the "presumption of innocence".

> "The presumption of innocence," writes Askin, "consists, as is well known, in the fact that a person is not required to prove his innocence; those who accuse him must prove that he is guilty, and until this is proven he is not considered guilty. In exactly the same way in science: until it is specifically proven that a given regularity is limited within certain bounds owing to certain circumstances, there exists no prohibition against the right to extrapolate it."

An interesting point of view, is it not?



On the other hand, Professor Vladimir Svidersky of Leningrad University objects to such unrestricted (global) extension of physical laws to "the whole material world in general". In his view, cosmology cannot claim the role of a science of the world as a whole — that role belongs to philosophy, and only philosophy should resolve questions concerning the finitude or infinitude of the world. With

the problem posed in this way, cosmology is left merely the role of a particular theoretical discipline.

Here we are confronted with two extreme positions. Yet other views also exist.

Academician Gustav Naan, in his substantial and highly interesting article *The Concept of Infinity in Mathematics and Cosmology*, writes:

> "The concept of infinity cannot be derived directly from physical phenomena. All the more interesting, therefore, is it to compare the conclusions of mathematics — which is most closely connected with the concept of infinity — with those physical phenomena of which they might serve as a description. The greatest possibilities for this are provided by phenomena on a cosmological scale."

In this book, from the very beginning, philosophy and the exact sciences have been seated at a round table, thereby deliberately emphasising the equality of the participants. Yet equality does not in the least remove the sharpness and seriousness of the problem: who is to concern himself with what? What is the prerogative of philosophy, and what belongs to natural science?

Academician Vitaly Ginzburg writes of a necessary "demarcation" of spheres of inquiry:

> "When a philosopher reflects upon a problem connected with natural science, it seems to me that he must first ask himself whether the given problem is philosophical or one of natural science?...
>
> ...The materialist position in cosmology consists in

> recognising the existence of the universe entirely independently of human cognition and, in fact, prior to its appearance. Moreover, bearing in mind not only subjective idealism but also objective idealism and religion, we emphasise that the materialist denies the existence of God and, in general, of anything 'standing behind' nature, 'giving rise' to the universe, and so forth. To the domain of philosophy belong, in addition, questions of methodology and of the theory of knowledge...
>
> ...Questions, however, as to whether space is Euclidean or non-Euclidean, whether its volume is finite or infinite, whether the universe is stationary or non-stationary, and by what laws the motion of galaxies is governed — all this belongs to the sphere of physics and astronomy, is based upon observation and experiment, and is controlled by them."

In addressing the question of the infinity of the world in space and time, Lenin's principle of the inexhaustibility of matter possesses considerable heuristic significance. As the Soviet philosopher Alexander Mostepanenko maintains, from the principle of the qualitative and quantitative inexhaustibility of matter there follows the proposition that the world contains a diversity of space–time forms and relations with different metric and topological properties. Consequently, the infinity of the world cannot be reduced to metric (purely quantitative) infinity alone.

In recent years, extragalactic astronomy has presented cosmologists with such unexpected findings that it has compelled a heightened interest in the topological (quali-

tative) structure of space–time.

The author ventures to remind the reader that topology is the branch of mathematics which studies those properties of figures that remain unchanged under all possible deformations, except tearing and gluing. The simplest example of a topological property of a geometric figure is its dimensionality — the number of dimensions. Thus a line is one-dimensional, a surface has two dimensions, and a solid has three.

Another topological property is the "order of connectedness", which depends on the number of "holes" in a geometric object. A torus (a ring-shaped surface) has a higher order of connectedness than, for example, a sphere or a plane, which have no holes. Matters become still more complex — and correspondingly less intuitive — when one considers the topological properties of space–time.

It is precisely in recent years that serious and "well-founded concerns" have arisen among specialists that the topological structure of space–time may be far more complex than previously assumed. For example, as Gustav Naan writes, "space may be multiply connected. Other 'pathologies' may also exist. In this case, the customary formulation of the problem of infinity in relativistic cosmology proves clearly insufficient."

It is not excluded that the world contains many different space–time forms, which may be either finite or infinite, and that for some of them the very notion of metric finitude or infinitude may be altogether inapplicable. It is also

possible that the hypothesis of the non-uniqueness of our metagalaxy has a right to exist. Yet in any case, the question of the metric finitude or infinitude of our metagalaxy must be decided not by philosophy but by empirical natural science.

And what of the "beginning" — the very first moment of the existence of our universe? How, from the standpoint of materialism, is one to reconcile oneself to the "emergence of an expanding universe from zero volume"?

If our concept of the universe truly referred to the world as a whole, to everything that exists, then it would indeed be difficult to resolve the question of its origin from a materialist standpoint. For if matter were "created", and if apart from matter in its various forms of manifestation nothing else material existed, then the initial principle could only have been "spirit".

However, since there are no grounds for identifying our metagalaxy with the world as a whole, the idealist conception is unwarranted.

We are convinced that the world does not arise out of nothing. "Creation" may be understood as a qualitative leap — a transition of matter from one state to another. The fact that theory is not yet able to give an unambiguous answer to this question merely signifies that this process, for the present, evidently lies beyond the domain of applicability of contemporary science. In discovering new laws, the natural scientist may and indeed must endeavour to extend their sphere of application, to extrapolate conclusions as far as possible. Yet philosophers must continually remind

him that such laws and extrapolations are not without limits.

> "The universe, as an object of cosmology," writes the Soviet philosopher Vladislav Kazutinsky, "in fact embraces the integral aspect of 'all that exists' not in an absolute sense, but in relation to a definite level in the development of human practice. In that case, this concept will develop dynamically together with science, and any 'miracles' of theory and observation will merely enrich our knowledge."

That which we today consider non-existent will tomorrow be discovered, will thus become existent from the scientific point of view, and will be included in our concept of the universe.

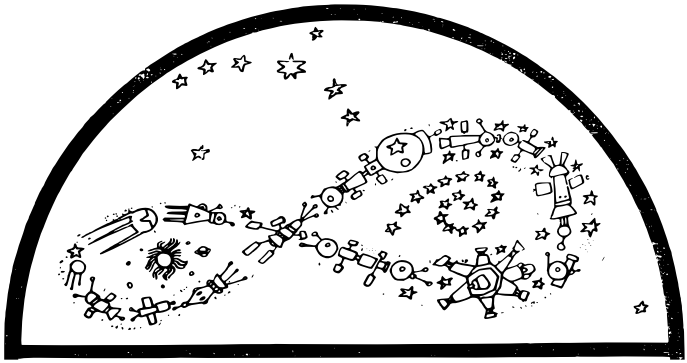
At this point the author would wish to conclude the final chapter of his book, aligning himself with the latter of the views considered concerning the prospects for the development of cosmology. All the more so because, in the author's opinion, they proceed directly from Lenin's understanding of the subject and methods of scientific knowledge.

> "The 'essence' of things, or 'substance', is also relative," wrote Vladimir Lenin. "They express only the deepening of human knowledge of objects; and if yesterday this deepening did not go beyond the atom, and today it goes beyond the electron and the ether, then dialectical materialism insists on the temporary, relative, approximate character of all these milestones in the cognition of nature by the progressing science of man. The electron is as inexhaustible as the atom; nature is infinite..."

Part IV.

Epilogue: Cosmology as of 2026

11. The Dark Side of the Cosmos



In which the reader confronts a universe far heavier and more hurried than once supposed, discovers that the "empty" void is actually a crowded darkness, and finally realizes that the more precisely we measure the cosmos, the more it eludes our grasp — leaving the seeker at a new beginning, where the only thing certain is that the mystery has grown.

Damitr Mazanav

When the book you are reading was published in 1971, the universe was a relatively tidy place. We had the Big Bang (thanks to Gamow and Lemaître), we had stars, and we

had galaxies and quasars. The assumption was simple on which most of science is based: what you see is what you get. If a galaxy looks like a swirling collection of stars, then those stars — and the gas between them — must constitute the total mass of that galaxy. It was a "well-arranged" world, as Kozma Prutkov might have appreciated.

From 1971 to today in 2026, more than half a century later, new discoveries have fundamentally changed our ideas of cosmology. We now look at some of these path-breaking discoveries which have redefined our understanding of the universe, its origin and fate.

11.1 The Mystery of the Missing Mass

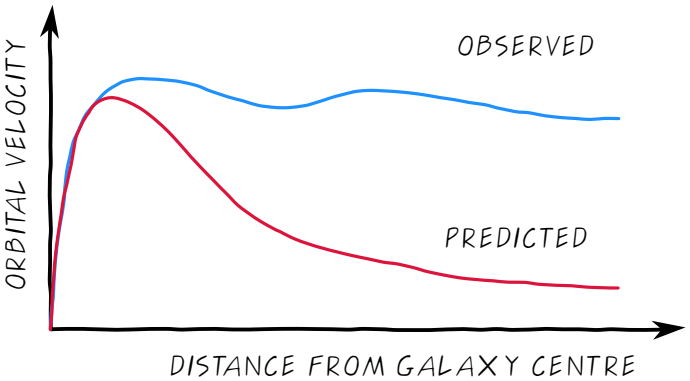
The hero of this story is American astronomer Vera Rubin. In the late 1960s and early 70s, Vera was a researcher at the Carnegie Institution's Department of Terrestrial Magnetism. Physics at the time was an old boys' club; Vera had been told earlier in her career that "women don't do astronomy" and was famously barred from the Palomar Observatory because it lacked a women's restroom (she reportedly taped a skirt-shaped piece of paper over the "Men" sign and went to work anyway).

Rubin teamed up with Kent Ford, an expert in instrumentation who had developed an incredibly sensitive image tube spectrograph. This device allowed them to take the light from distant galaxies and split it into frequencies

with unprecedented precision. They pointed their telescope at M31[41] (The Andromeda Galaxy), looking not at its center, but at its outermost edges.

[41] "M" refers to the Messier Catalogue compiled by Charles Messier, and "31" is its entry number. – DM

According to the laws of physics established by Isaac Newton, the speed at which an object orbits a center of mass depends on how much mass is inside that orbit. In a galaxy, the vast majority of visible light comes from the center. Naturally, astronomers expected that stars at the edges of a galaxy would move much slower than the stars in the center.



However, as Rubin and Ford plotted their data, they saw something that shouldn't be possible. The rotation curve didn't drop off. It stayed flat. The stars at the edge were moving just as fast as the stars near the center. By all the laws of gravity, those stars should have been flung out into the intergalactic void like mud off a spinning bicycle tire.

The only logical conclusion was that there was "something" out there providing extra gravity — something that didn't emit light, reflect light, or block light. This was fittingly termed as *Dark Matter*.

Rubin wasn't actually the first to suggest this term. In 1933, a brilliant but cantankerous Swiss-American astronomer named Fritz Zwicky at Caltech had looked at the Coma Cluster of galaxies. He noticed they were moving too fast to stay bound together and claimed there must be *Dunkle Materie* (Dark Matter) holding them in. But Zwicky was known for calling his colleagues "spherical bastards" (because they were bastards no matter which way you looked at them), and his ideas were largely dismissed as the ramblings of an eccentric.

It was Rubin's meticulous, undeniable data that finally forced the scientific community to come to terms with this impossibility. By the late 1970s, it became clear that galaxies aren't just collections of stars; they are tiny "islands" of light trapped in massive, invisible "halos" of Dark Matter.

Since 1971, the search for what Dark Matter *actually is* has moved from telescopes to underground laboratories. We now know that it isn't just cold gas or dead planets (which we call MACHOs — Massive Compact Halo Objects). The leading theory is that it consists of WIMPs (Weakly Interacting Massive Particles).[42]

To find them, institutions like CERN in Switzerland (using the Large Hadron Collider) try to smash particles together to create them, while facilities like the Sanford Un-

[42] If a phenomenon resists understanding, we tend to give it an fancy acronym — it will at least appear more manageable. – DM

derground Research Facility in USA use the LUX-ZEPLIN experiment — a giant vat of liquid xenon buried a mile underground — hoping to catch a single Dark Matter particle bumping into an atom.

As of 2026, we have measured the "unmeasurable" mass of the universe, only to find that *85% of all matter is something we cannot see, touch, or identify*. It is the "Hidden Hand" that sculpted the large-scale structure of the cosmos. As Prutkov might have warned: "If you find a thing that is not there, do not assume it is empty; it may simply be shy." Perhaps some of you who are reading this will be the ones to find out what this "dark matter" is.

11.2 A Hi-Res Echo of the Beginning

In the 1971 edition of this book, the "Great Explosion" — or the Big Bang — was a compelling theory, but it lacked a detailed map. Astronomers knew the universe began in a hot, dense state because Arno Penzias and Robert Wilson had accidentally stumbled upon a persistent "hiss" in their horn antenna at Bell Labs in 1964. They had found the Cosmic Microwave Background Radiation (CMBR), the afterglow of the Big Bang. But to the telescopes of 1971, this glow looked perfectly smooth. And in cosmology, "perfectly smooth" is a massive problem.

If the early universe had been perfectly uniform, like a smooth bowl of soup, gravity would have had nothing to

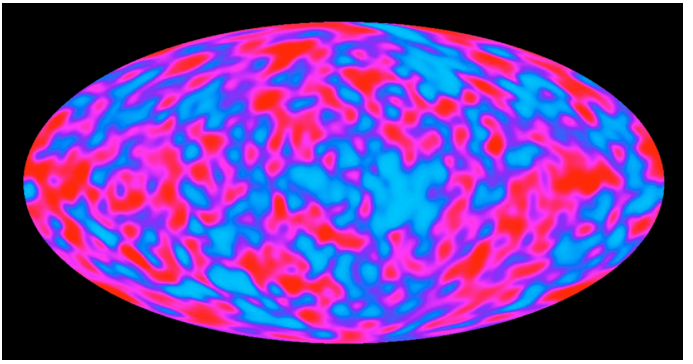
grip onto. There would be no clumps, no stars, no galaxies, and — crucially — no authors or readers to discuss them. For the "well-arranged" universe to exist today, the infant universe *must* have been slightly "lumpy". We needed to find those "lumps" in that ancient light, but they were so faint that the Earth's atmosphere blocked them entirely. We had to go to space.

Our atmopshere allows certain raditions to pass through while blocking others. Visible light, and a few narrow windows in the radio spectrum, reach the ground with relative ease, which is why early astronomy was confined to what could be seen or detected from Earth. But much of the universe speaks in other wavelengths — microwave, infrared, ultraviolet, *X*-ray — and these are absorbed, scattered, or drowned in atmosphere long before they reach our instruments.

The faint irregularities in the relic radiation of the early universe lie precisely in one of these obscured bands. To detect them required lifting our detectors above the distorting blanket of air, into the clarity of space. Only in space the background itself could be measured with the necessary precision.

In 1989, NASA launched the Cosmic Background Explorer (COBE). Led by John Mather and George Smoot, this mission was designed to measure the temperature of the CMBR with unprecedented accuracy. In 1992, the team announced a bombshell: they had found the ripples. After removing other known sources of radiation, COBE data

revealed tiny variations in the temperature of the cosmic microwave background — the oldest light in the universe — for the first time. In the figure shown next, red indicates hotter regions, blue colder. The central plane of our galaxy runs across the middle of this all-sky image. The fluctuations are extremely faint, varying by only 1 part in 100,000 from the average temperature. These variations represent an imprint of the density difference in the early universe. These variations are thought to be the "seeds" of the modern cosmos, giving rise to the structures that populate the universe today.

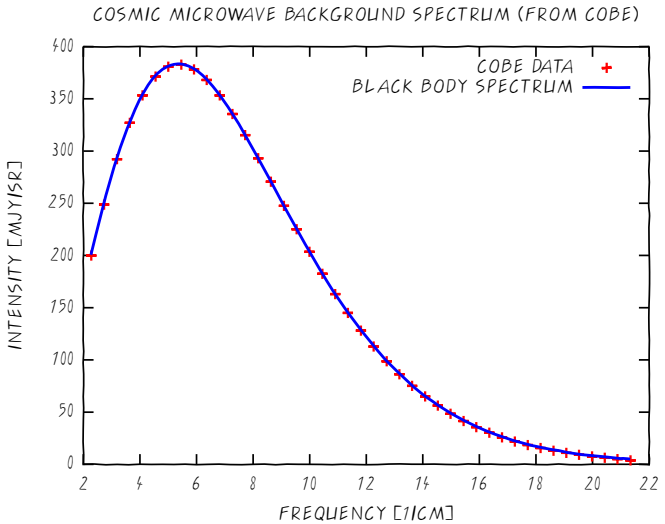


Smoot famously (and controversially) remarked that if you're religious, it's like "looking at the handwriting of God." These fluctuations, often called "anisotropies"[43], showed exactly where gravity had begun to pull matter together to build the first galaxies. Mather and Smoot would eventually share the Nobel Prize in 2006 for this work, but COBE

[43] From Greek *an-* ("not") + *isos* ("equal") + *tropos* ("direction"): literally "not the same in all directions", the opposite of isotropy (uniformity in every direction); here referring to the tiny directional variations in the cosmic microwave background measured by COBE. – DM

was only the beginning of our quest to "measure the immeasurable" heat of creation.

Data from COBE showed in the graph below is a near perfect fit between the black body curve predicted by big bang theory and that observed in the microwave background. The error bars are smaller than the width of the blue curve. The red crosses merely locate the data points. (Modified from a graph by Quantum Doughnut, Public Domain.) This might be one of the graphs in which theory and observations fit perfectly!



COBE did more than merely confirm that the back-

ground radiation existed; it established that the universe, on the largest scales, obeys a remarkably simple thermal order. The radiation follows an almost perfect blackbody spectrum, exactly as expected from a hot, dense origin. This was not a vague agreement but a precise one: deviations, if any, were too small to be detectec. In effect, COBE closed the door conclusively on many alternative cosmologies that could not reproduce such an equilibrium spectrum. The Big Bang was no longer just plausible — it became, in a strict physical sense, unavoidable.

Equally significant was the scale and character of the anisotropies themselves. They were not random blemishes but exhibited a statistical pattern consistent with tiny quantum fluctuations stretched to cosmic proportions in the earliest moments of the universe. This provided the first observational foothold for ideas such as cosmic inflation, suggesting that the vast structures we see today — clusters, filaments, and voids — grew from minute irregularities imprinted when the universe was less than a second old. The largest features in the map correspond to fluctuations spanning immense regions of space, hinting at a universe that was already correlated over distances far exceeding naïve expectations.

Yet, if COBE answered some questions, it sharpened others. The ripples it detected were too large in scale and too coarse in detail to explain how galaxies formed in practice. They were the first sketch, not the finished drawing. To understand the finer structure — the acoustic peaks, the precise geometry, the composition of matter and en-

ergy — more sensitive missions would be required. COBE thus marked a turning point: cosmology ceased to be a largely speculative discipline and became a precision science, where the history of the universe could be read, line by line, in the faint afterglow of its birth.

11.3 WMAP and the Age of Precision

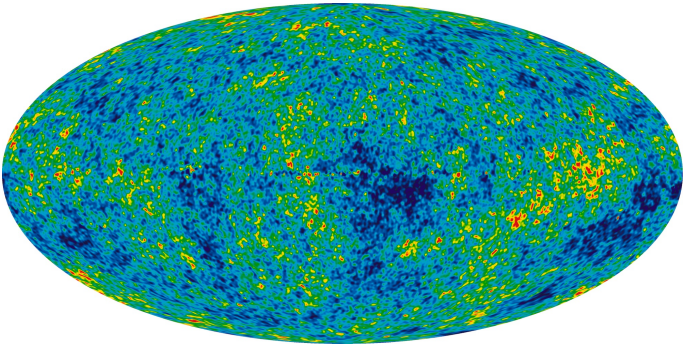
If COBE gave us a blurry polaroid, the Wilkinson Microwave Anisotropy Probe (WMAP)[44], launched in 2001, gave us a high-definition portrait. Operating from the Lagrange Point 2 (L2) — a stable spot in space a million miles away from Earth — WMAP allowed cosmologists to more precise measurements of CMBR.

[44] David Todd Wilkinson (1935–2002), a pioneer of cosmic microwave background research and member of the COBE science team; the probe was named in his honour following his death, recognising his contributions to precision cosmology. – DM

By analyzing the size and distribution of the ripples in the CMB, the WMAP team (including pioneers like David Spergel and Charles Bennett) calculated the age of the universe with staggering precision: 13.7 billion years (later refined to 13.8). They confirmed that the universe is "flat" in the Euclidean sense — meaning the triangles Euclid actually hold true on the largest scales — and they also pinpointed the exact moment the first stars began to shine.

WMAP, thus did not simply sharpen the picture — it made the universe measurable at the earliest times and the largest scales. The fine structure of the anisotropies revealed a distinct pattern of peaks and troughs, encoding the physics of the early universe when matter and radi-

ation were tightly coupled as shown in the image below. From these acoustic signatures, cosmologists could determine not just geometry, but the contents of the cosmos. Ordinary matter was found to make up only a small fraction, with the rest divided between dark matter and the even more enigmatic dark energy.



One-year WMAP image of background cosmic radiation. Colors indicate "warmer" (red) and "cooler" (blue) spots. The oval shape is a projection to display the whole sky, similar to the way the globe of the Earth can be represented as an oval. The microwave light captured in this picture is from 379,000 years after the Big Bang, over 13 billion years ago. Credits NASA/WMAP Science Team, Public Domain image.

Equally important was the confirmation of a deeper theoretical idea: that the structure of the universe arose from tiny quantum fluctuations stretched to cosmic scales in an early epoch of rapid expansion. The statistical properties of the CMB fluctuations — their near-uniformity with slight, scale-dependent deviations — matched the predictions of simple *inflationary models* with remarkable accuracy. What had once been a bold theoretical proposal now rested on firm observational ground.

Yet WMAP's legacy lies as much in what it enabled as

in what it measured. By fixing the basic parameters of the universe with high precision, it transformed cosmology into a tightly constrained science. Later missions would refine these numbers further, but the essential framework — a flat, expanding universe dominated by dark components and seeded by primordial fluctuations — was already firmly in place.

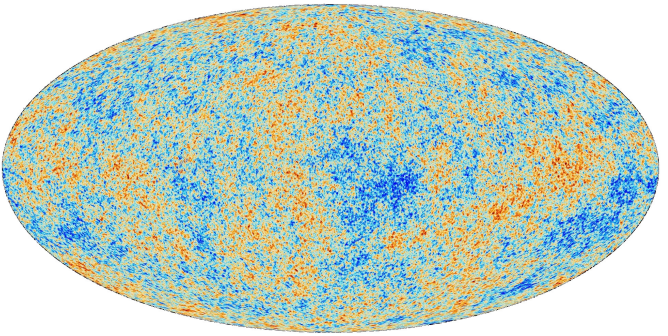
11.4 Planck: The Ultimate Map (So far...)

The final word in this trilogy came from the European Space Agency (ESA) and the Planck Satellite (2009–2013). Planck was the "super-microscope" (or should it be called "super-telescope"?) of the heavens. It mapped the CMBR with such incredible resolution that it could detect temperature differences of millionths of a degree as shown in the image.

The data from Planck, processed at institutions like the Max Planck Institute for Astrophysics and Caltech, provided the "Standard Model of Cosmology". It told us exactly what the cosmic "recipe" was: about 5% normal matter, 27% dark matter, and 68% dark energy.

What Planck was actually measuring were "acoustic oscillations". When the universe was a hot plasma soup, there was a tug-of-war between the inward pull of gravity and the outward push of radiation pressure. This created sound waves that rippled through the cosmos. When

the universe cooled down enough for light to travel freely (about 380,000 years after the Big Bang), these sound waves were "frozen" into the light.



Temperature map of the cosmic microwave background measured by the Planck spacecraft. This map of the Cosmic Microwave Background radiation, imprinted on the sky when the universe was 370,000 years old, shows tiny temperature fluctuations that correspond to regions of slightly different densities. Credits ESA and the Planck Collaboration Cosmic Microwave Background, CC BY 4.0.

In the language of physics, the temperature we measure today is:

$$T_{CMB} = T_{emit}\left(\frac{1}{1+z}\right)$$

Where T_{emit} was a scorching 3,000 K, but because the universe has expanded, it has been redshifted (z) down to a chilly 2.725 K.

As Anatoly Tomilin noted in earlier chapters, the "immeasurable" becomes measurable once you have the right tools. We have gone from wondering if the Big Bang happened to having a high-resolution "baby picture" of the moment light first broke free from the darkness. As Kozma

Prutkov might say: "The past is never dead; it is just very far away and slightly cold."

A comparative illustration of how the three space-telescopes differ in resolution is shown in the figure next.

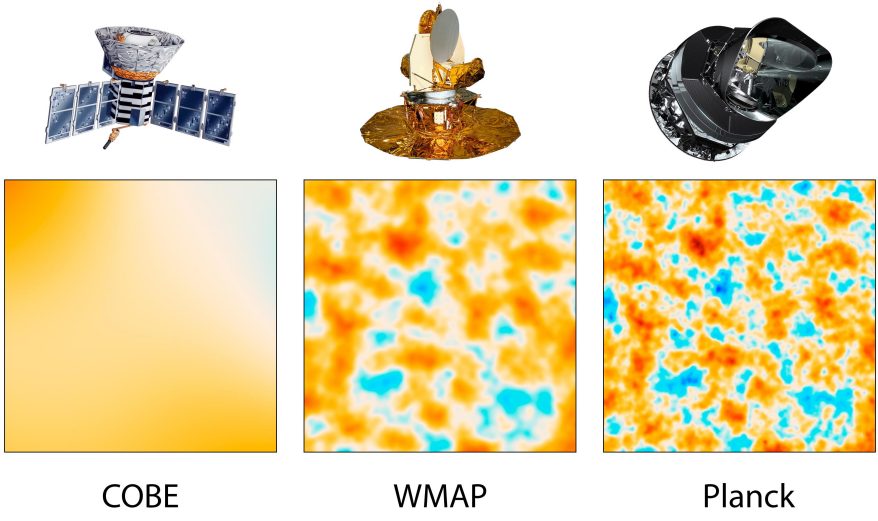


Image (Courtesy NASA/JPL-Caltech, CC BY Attribution)

The three panels show 10-square-degree patches of all-sky maps created by space-based missions capable of detecting the cosmic microwave background. The tiny variations, called anistotropies, in the ancient light reveal information about the state of the universe. After COBE detected them in 1989 (left panel), the variations came into

sharper focus with the Wilkinson Microwave Anisotropy Probe in 2001, or WMAP (middle panel). WMAP found strong evidence for inflation, the very early epoch in our universe when it expanded dramatically in size, and measured basic traits of our universe better than ever before. Planck, launched in 2009, images the sky with more than 2.5 times greater resolution than WMAP, revealing patterns in the ancient cosmic light as small as one-twelfth of a degree on the sky. Planck has created the sharpest all-sky map ever made of the universe's cosmic microwave background, precisely fine-tuning what we know about the universe.

11.5 Seconds after the Bang

By the late 1970s, the Big Bang theory had a few "skeletons in the closet" that the 1971 version of this book couldn't quite explain. These were known as the *Flatness Problem* and the *Horizon Problem*. To put it simply: the universe was too perfect. It was too flat, and parts of the sky that had never been in contact with each other were at the exact same temperature. It was as if two people on opposite sides of the planet had both decided, at the exact same second, to do exactly something obscure in same order without ever speaking.

In 1979, a young physicist named Alan Guth, then a postdoc at Stanford, was working on something called Grand Unified Theories (GUTs). He realized that in the very first

moments of the universe — roughly 10^{-36} seconds after the beginning — there could have been a phase transition[45] that caused space to expand exponentially.

He called it *Inflation*. In a very small time, the universe grew from something smaller than a subatomic particle to something roughly the size of a grapefruit. This expansion was so violent and so fast that it smoothed out all the "wrinkles" in space, much like blowing up a balloon makes the surface appear perfectly flat. This solved the Flatness Problem and ensured that the entire visible universe started from one tiny, connected point, solving the Horizon Problem.

The Physics of the Inflaton. Guth's theory was based on a hypothetical field called the *inflaton field*. This field possessed a "false vacuum" state with a high energy density that exerted a repulsive pressure — a bit like the Dark Energy we discussed in the previous section.

As the field "decayed" to a lower energy state, the expansion stopped, and the leftover energy was dumped into the universe, creating the "hot soup" of particles that we recognize as the traditional Big Bang. This led Guth to famously call the universe "the ultimate free lunch". Everything we see — all the billions of galaxies — could have originated from just a few ounces of "starting material" amplified by the vacuum.

For decades, Inflation was a beautiful mathematical dream. To prove it, we needed to find "Primordial Grav-

system when conditions cross a critical threshold — like water freezing into ice. In the early universe, these transitions involve quantum fields rather than substances, and can release energy that drives rapid expansion. – DM

itational Waves" — ripples in spacetime created by that sudden, violent burst. These ripples would leave a specific "swirly" pattern (the so-called *B*-mode polarization) in the CMBR.

Major facilities were built in the harshest environments on Earth to look for this, most notably the BICEP (Background Imaging of Cosmic Extragalactic Polarization) telescopes and the South Pole Telescope at the Amundsen–Scott South Pole Station. In 2014, the BICEP2 team thought they had found it, but it turned out to be cosmic dust from our own galaxy (a reminder that measuring the immeasurable requires extreme caution).

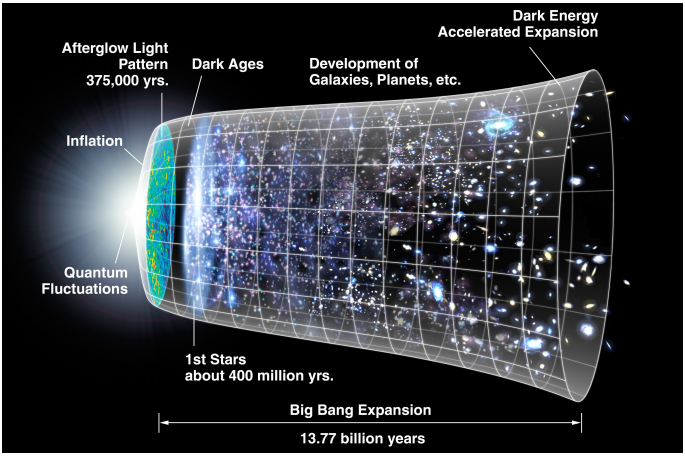
However, the Planck Satellite data has provided indirect evidence that is incredibly consistent with Inflation, particularly in how it predicted the exact distribution of the "lumps" in the early universe. The "madness" of Inflation doesn't stop with our universe. Scientists like Andrei Linde and Alex Vilenkin realized that if Inflation happened once, it might be happening all the time. This is the theory of "Eternal Inflation", which suggests that our universe is just one "bubble" in a vast, foaming sea of other universes — the Multiverse.

In this view, the "laws of physics" we've discussed in every chapter so far might just be local "bylaws" for our specific bubble. Elsewhere, gravity might be repulsive, or light might not exist at all.

The image next shows the timeline of the universe with inflation and dark energy taken into account. A represen-

tation of the evolution of the universe over 13.77 billion years. The far left depicts the earliest moment we can now probe, when a period of "inflation" produced a burst of exponential growth in the universe. For the next several billion years, the expansion of the universe gradually slowed down as the matter in the universe pulled on itself via gravity. More recently, the expansion has begun to speed up again as the repulsive effects of dark energy have come to dominate the expansion of the universe. The afterglow light seen by WMAP was emitted about 375,000 years after inflation and has traversed the universe largely unimpeded since then. The conditions of earlier times are imprinted on this light; it also forms a backlight for later developments of the universe.

Credits NASA, Public Domain.



A Prutkovian Conclusion. If we take the "wise counsel" of Kozma Prutkov regarding the immeasurability of the immeasurable, Inflation is the ultimate test. We are trying to measure a moment that happened

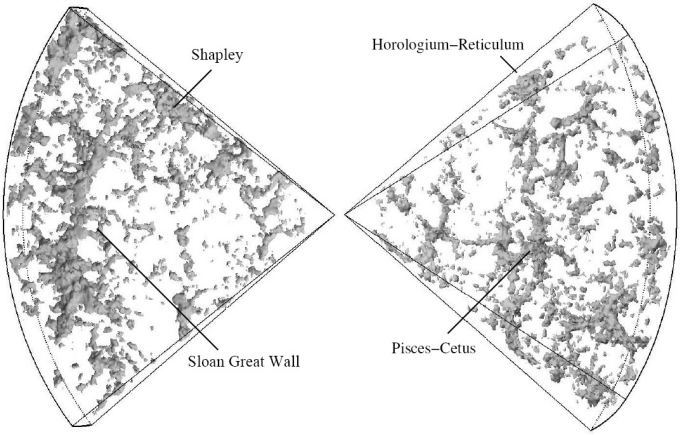
0.000 000 000 000 000 000 000 000 000 000 000 001

seconds after the start. As Prutkov might have sighed: "One cannot grasp the ungraspable, especially when it is moving faster than light and doubling in size every trillionth of a second."

11.6 The Cosmic Web: The Universe Draws Its Own Map

If Rubin showed us that galaxies are heavier than they appear, and COBE revealed that the early universe was not perfectly smooth, a crucial question still remained. How did the tiny ripples in the infant cosmos grow into the vast structures we see today? Between the initial "seeds" and the present universe lay a missing chapter — the large-scale structure of the cosmos.

In the closing years of the 20th century, astronomers began an ambitious shift in perspective. Instead of studying galaxies individually, they sought to map their *distribution across immense volumes of space*. The aim was simple in formulation but profound in consequence: to see the universe as a whole, single unit.



Three-dimensional reconstruction of the inner parts of the 2dF Galaxy Redshift Survey. The figure reveals an impressive view of cosmic structure in the nearby universe. Several superclusters are visible. Credits Willem Schaap, CC BY-SA 3.0

One of the first major steps in this direction was the **2dF** Galaxy Redshift Survey at the Anglo-Australian Observatory. 2dF here stands for "2-degree Field", referring to the innovative spectrograph used in this survey. This instrument could simultaneously capture spectra from up to 400 galaxies within a 2-degree diameter field of view on the sky (roughly 4 full Moons wide). Each fiber optic cable fed light from a selected galaxy to the spectrograph, enabling efficient redshift measurements across large sky patches.

The 2dF Galaxy Redshift Survey between 1997 and 2002 measured redshifts for over 245,000 galaxies brighter than magnitude 19.45, creating the first large-scale 3D map out to redshift $z \approx 0.3$. By measuring the redshifts of hundreds

of thousands of galaxies, it provided one of the earliest three-dimensional maps of the nearby universe.

What emerged from this and similar surveys was unexpected in its clarity. Galaxies were not scattered randomly, nor simply clustered in isolated groups. Instead, they traced out a vast network of filaments and sheets, surrounding enormous empty regions known as voids. This structure — now called the *cosmic web* — extends across hundreds of millions of light-years, forming a universe that resembles a three-dimensional foam rather than a collection of isolated islands.

11.7 The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS) later extended this picture dramatically. Using a dedicated 2.5-metre telescope at Apache Point Observatory in Nex Mexico, USA, it mapped millions of galaxies with unprecedented uniformity and depth. By assigning each galaxy a redshift, and therefore a distance, SDSS transformed the earlier glimpses of structure into a detailed and statistically robust three-dimensional atlas.

With this vastly expanded dataset, the cosmic web ceased to be merely a visual impression and became a measurable entity. Astronomers could quantify how galaxies cluster, how this clustering depends on scale, and how it evolves over cosmic time. On the largest scales, the observed struc-

ture provided compelling evidence that ordinary matter alone could not account for the formation of such vast networks. The growth of structure from tiny initial fluctuations requires gravitational amplification over billions of years, driven predominantly by a non-luminous component. Dark matter, first inferred within galaxies, now revealed itself as the scaffolding of the universe as a whole.

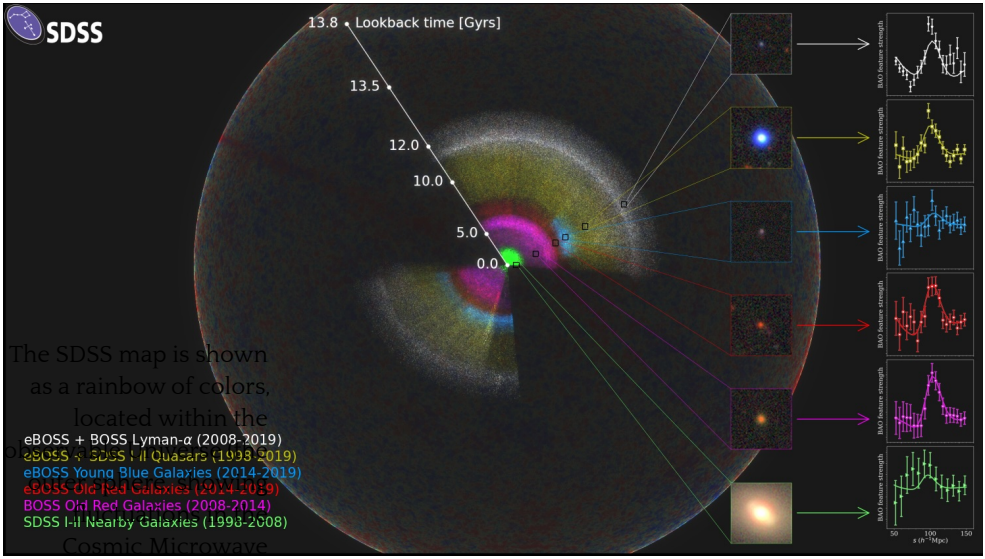
Within this statistical description of galaxy clustering lay an even subtler discovery. The distribution of galaxies showed a slight but consistent preference for separations of a particular scale — about 150 megaparsecs. This feature, known as baryon acoustic oscillations (BAO), is a relic from the early universe.

Before atoms formed, matter and radiation were tightly coupled in a hot plasma, through which pressure waves — sound waves — propagated. When the universe cooled and radiation decoupled, these waves were effectively frozen into the matter distribution. Billions of years later, their imprint remains detectable in the large-scale arrangement of galaxies.

These oscillations provide a powerful tool: a standard ruler. Because the physical scale of these primordial waves is well understood, measuring how this scale appears at different epochs allows cosmologists to trace the expansion history of the universe.

The figure shown next is a SDSS map of galaxy distribution. We are located at the center of this map. The inset for each color-coded section of the map includes an image of

a typical galaxy or quasar from that section, and also the signal of the pattern that is measuresed there. As we look out in distance, we look back in time. So, the location of these signals reveals the expansion rate of the Universe at different times in cosmic history.



The SDSS map is shown as a rainbow of colors, located within the Cosmic Microwave Background). Credits Anand Raichoor (EPFL), Ashley Ross (Ohio State University) and the SDSS Collaboration CC BY-SA 4.0

The significance of large-scale structure is therefore twofold. First it demonstrates, on the largest observable scales, that dark matter dominates the formation of cosmic structure. Second, it preserves a memory of the early universe, linking the fluctuations seen in the cosmic mi-

crowave background to the distribution of galaxies we observe today.

In this sense, the cosmic web forms the missing bridge in modern cosmology. It connects the initial conditions revealed by the CMB, the invisible mass inferred from galaxy dynamics, and the expansion history later uncovered through supernova observations. Without this bridge, these elements remain disconnected. With it, they form a coherent narrative of a universe evolving from minute fluctuations into a vast, structured cosmos.

As Kozma Prutkov might have observed: "If you wish to understand a forest, do not count the leaves — look at the pattern of the trees."

11.8 Dark Energy and the Runaway Universe

In 1971, the ultimate fate of the universe seemed to be a simple binary choice, much like a ball thrown into the air. Either the ball (the universe) had enough velocity to escape Earth's gravity and fly off forever, or gravity would eventually win, slowing the ball down until it stopped and plummeted back to the ground. In cosmological terms, this was the "Big Crunch" versus the "Big Freeze". Everyone assumed that the expansion of the universe was slowing down. The only question was *how much*.

The Cosmic Standard Candles. To answer this, astronomers needed a way to measure distances across billions of light-years. They found their answer in Type Ia Supernovae. These are the spectacular explosions of white dwarf stars that have sucked too much matter from a companion star. Supernovae are classified by their spectra and light curves: Type I lack hydrogen lines, while Type II show them. Type I is further divided into Ia, Ib, and Ic: Type Ia arise from thermonuclear explosions of white dwarfs in binary systems, whereas Types Ib and Ic result from the core collapse of massive stars that have lost their outer layers; Type II supernovae are core-collapse events of massive stars retaining hydrogen. Because they all explode at the same critical mass (the Chandrasekhar limit)[46], they all shine with roughly the same intrinsic brightness. They are the "standard candles" of the cosmos. If you know how bright a light bulb is, you can calculate exactly how far away it is by measuring how dim it looks.[47]

[46] The Chandrasekhar limit (∼ 1.4 solar masses) is set by the competition between gravity and electron degeneracy pressure, a quantum effect arising from the Pauli exclusion principle. As mass increases, this pressure becomes insufficient to counter gravity, and the star collapses. – DM

In the mid-1990s, two separate teams set out to use these stellar explosions to measure the "deceleration parameter" of the universe. The Supernova Cosmology Project, led by Saul Perlmutter at Lawrence Berkeley National Laboratory, USA and the High-*Z* Supernova Search Team, led by Brian Schmidt (at the Australian National University) and Adam Riess (at the Space Telescope Science Institute).

[47] Standard candle — an object of known intrinsic brightness (luminosity); since observed brightness decreases with the square of distance, comparing the known luminosity with the measured brightness allows the distance to be calculated via the inverse-square law. – DM

The two teams in their efforts used some of the world's most powerful telescopes, including the 4-meter telescope at the Cerro Tololo Inter-American Observatory in Chile and the massive 10-meter Keck Telescopes in Hawaii. They

expected to find that *distant supernovae would be brighter* than their distance would suggest — a sign that gravity was successfully braking the expansion of the universe.

Instead, in 1998, both teams arrived at a conclusion so absurd they initially thought they had made a mistake: *The distant supernovae were fainter than expected*. They were further away than they should have been if the universe were slowing down. The expansion of the universe wasn't slowing; it was *accelerating*. It was as if that ball thrown into the air had suddenly ignited a rocket engine and screamed off into the stratosphere.

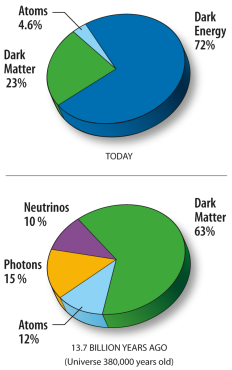
How do we make sense of this? To explain this "anti-gravity" effect, cosmologists had to reach back into history and pull out Einstein's "Cosmological Constant" (Λ), which he had famously called his "greatest blunder". Einstein had originally added Λ to his equations to keep the universe static (preventing it from collapsing under its own gravity). When Hubble proved the universe was expanding, Einstein tossed it. But the 1998 discovery proved that something like Λ was real — a "vacuum energy" that exists in empty space itself, pushing the universe apart.

This mysterious force was dubbed *Dark Energy* by theorist Michael Turner. Unlike matter, which thins out as space expands, Dark Energy appears to be a constant property of space. As the universe expands and creates more space, there is more Dark Energy, which causes even faster expansion — a runaway feedback loop.

The discovery of Dark Energy changed our "well-arranged"

1971 universe into a much lonelier one. If Dark Energy continues to dominate, the "Big Crunch" is off the table. Instead, the universe faces a "Big Freeze" (or even a "Big Rip"). Galaxies will be pushed so far apart that their light will never reach us. Eventually, the night sky of our distant descendants will be completely black, save for the stars within our own local cluster.

Today, the most precise measurements of this acceleration come from the Hubble Space Telescope and the Dark Energy Survey (DES) at the Victor M. Blanco Telescope in Chile. We have found that Dark Energy makes up a staggering 72% of the universe's total energy density. The figure on the right shows estimated distribution of different components in the universe.



WMAP data reveals that its contents include 4.6% atoms, the building blocks of stars and planets. Dark matter comprises 23% of the universe. This matter, different from atoms, does not emit or absorb light. It has only been detected indirectly by its gravity. 72% of the universe, is composed of "dark energy", that acts as a sort of an anti-gravity. This energy, distinct from dark matter, is responsible for the present-day acceleration of the universal expansion. WMAP data is accurate to two digits, so the total of these numbers is not 100%. This reflects the current limits of WMAP's ability to define Dark Matter and Dark Energy. (Credits: NASA / WMAP Science Team)

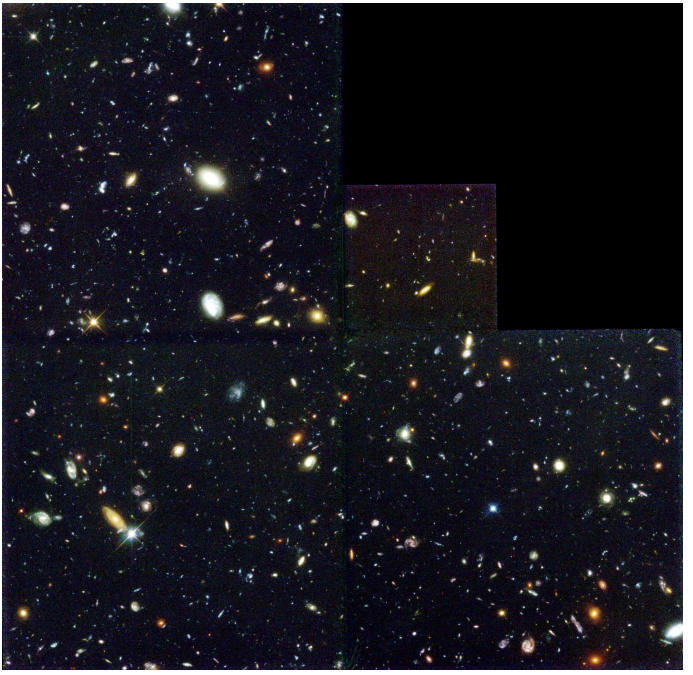
In the language of General Relativity, we now live in a Λ-CDM universe (Lambda plus Cold Dark Matter). The Λ term,

once zeroed out by Einstein, is now the most important number in physics, like a pheonix rising out from its ashes.

As Kozma Prutkov might have mused: "If you find the world is moving away from you faster than you can follow, perhaps it is not you who is standing still, but the world that has found a new reason to leave."

11.9 The Hubble Deep Field

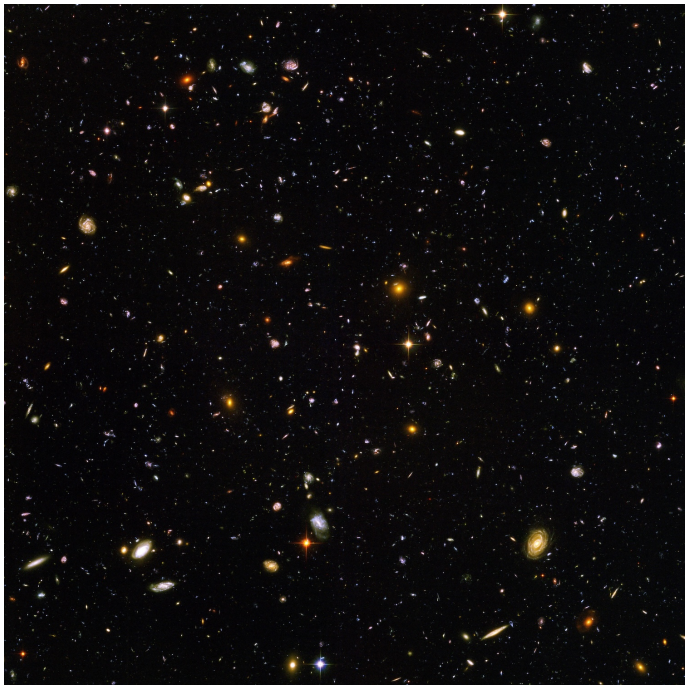
By taking telescopes in space, as was dreamt since the inception of satellites, some of the most stunning views of cosmos were revealed by the Hubble Space Telescope. Among the myriad of images that it has produced over last three decades one of the most iconic is the Hubble Deep Field (HDF). This image was captured over ten days in December 1995, remains a cornerstone of modern physical cosmology. This image transformed the study of galaxy evolution from theoretical modeling into direct observation. By pointing at a seemingly "empty" patch of sky for over 100 hours, Hubble revealed nearly 3,000 galaxies in various stages of development, some appearing as they were just half a billion years after the Big Bang.



The Hubble Deep Field showing about 3000 galaxies in a seemingly empty tiny region of space (1995). By Robert Williams (NASA, ESA, STScI) - Hubblesite.org, Public Domain, via Wikimedia.

HDF can be seen as a "fossil record" provided the first clear evidence that the early universe was a chaotic, high-energy environment where small, irregular protogalaxies frequently collided and merged to form the massive spiral and elliptical structures seen today. These observations effectively validated the hierarchical model of galaxy formation and laid the groundwork for subsequent "ultra-deep" (HUDF) surveys that now probe the "dark ages" of the early

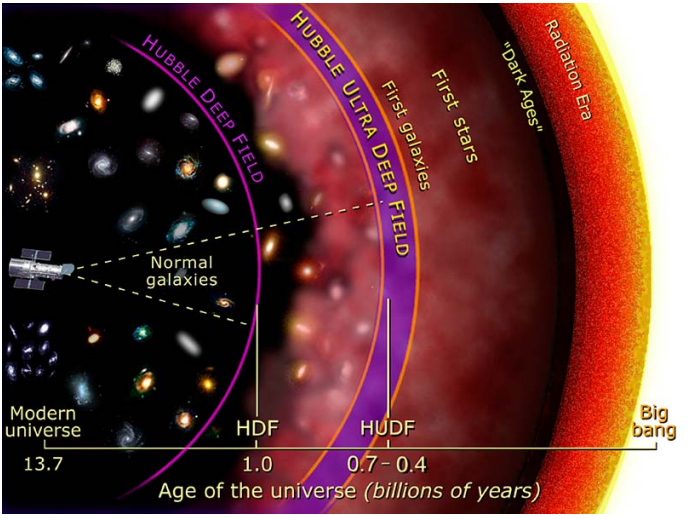
cosmos. In HUDF the image below contains about 10,000 galaxies of various ages, sizes, shapes, and colors. The smallest, reddest ones are some of the most distant galaxies to have been imaged by an optical telescope, probably existing shortly after the Big Bang.



The Hubble Ultra Deep Field showing about 10,000 galaxies in a seemingly empty tiny region of space (2003). Credits NASA and the European Space Agency. Edited by Noodle snacks - Hubblesite.org, Public Domain, via Wikimedia.

The image shown next explains how long back we are seeing the universe in the two images. While HDF looked

at galaxies formed at about a billion years from the Big Bang, the HUDF provides a view of even earlier epoch of 0.7-0.4 billion years from the Big Bang.



How back in time are HDF and HUDF are seeing? The image shows the 1995 Hubble Deep Field and the Hubble Ultra Deep Field from 2003 and 2009. Credits NASA, Public Domain, via Wikimedia.

Beyond its scientific utility, the deep field images had a profound cultural impact, fundamentally altering the public's visual conception of the universe. It shifted the popular image of "deep space" from a cold, dark void to a vibrant, crowded landscape teeming with islands of stars. The image's striking aesthetic—often compared to the 19th-century "sublime" landscapes of the American West—made the vastness of the cosmos accessible and awe-inspiring

to the general public. This visual revolution turned Hubble into a household name and integrated astronomical imagery into mainstream media, appearing in everything from high-budget science fiction films to daily consumer products like calendars and clothing. Ultimately, the HDF democratized the beauty of the universe, moving it from the exclusive domain of professional astronomers into the collective human consciousness.

Looking at these images of the deep field, Kozma Prutkov might stroke his chin and offer this wisdom: "If you see an empty space, do not believe your eyes; for even the smallest hole in the curtain of Night is but a window into a very crowded room."

11.10 Hearing the Black Holes

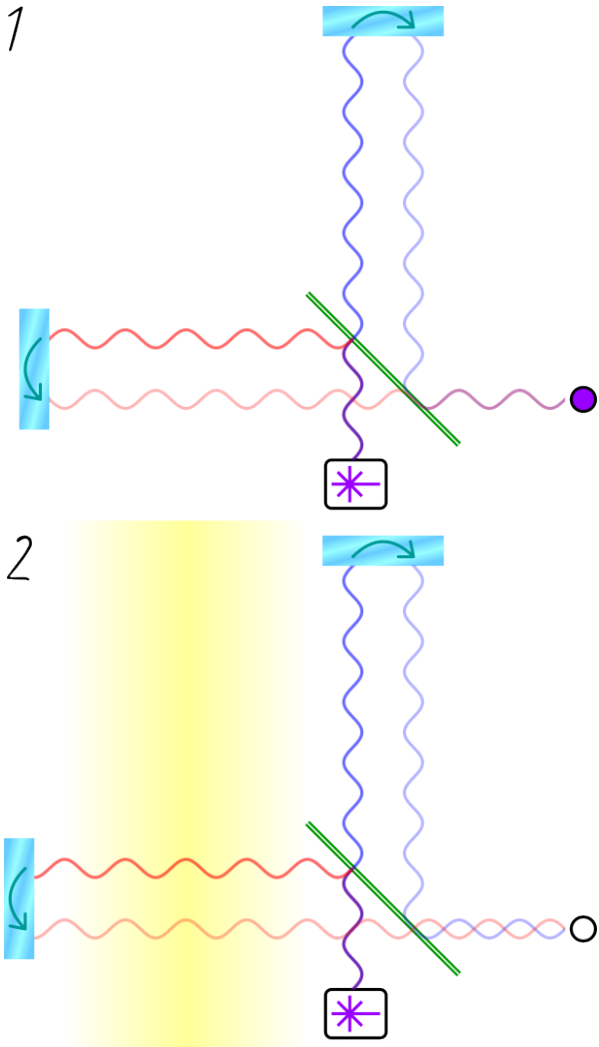
In the world of 1971, astronomy was a visual medium. For thousands of years, we had looked at the universe — first with the naked eye, then with glass lenses, and finally with radio dishes. But we were essentially watching a silent movie. Einstein had predicted in 1916 that space-time isn't just a static stage but a fabric that can ripple, but he also believed these "gravitational waves" were so incredibly faint that they would never be measured. To Einstein, these ripples were a mathematical curiosity, not a tool for observation.

The Impossible Measurement. Imagine a rod one kilometer long. A gravitational wave passing through it would change its length by a fraction of the width of an atomic nucleus. It is the definition of "measuring the immeasurable". To do this, we needed more than a telescope; we needed a "ruler" made of light.

Enter LIGO (Laser Interferometer Gravitational-Wave Observatory). This project, spearheaded by Kip Thorne (Caltech), Rainer Weiss (MIT), and Barry Barish (Caltech), involved building two massive, *L*-shaped detectors — one in Hanford, Washington, and the other in Livingston, Louisiana. Each arm of the "L" is four kilometers long. A laser beam is split and sent down both arms, reflected by mirrors, and recombined. If a gravitational wave passes through, it stretches one arm and squeezes the other, causing the light waves to shift out of alignment.

September 14, 2015: The Chirp. For decades, LIGO heard nothing but the "noise" of the Earth — passing trucks, distant ocean waves, and even the vibration of atoms in the mirrors. But on September 14, 2015, a signal arrived. It was a "chirp" — a wave that increased in frequency and amplitude for a fraction of a second before vanishing.

That signal, named GW150914, was the "sound" of two massive black holes, each about 30 times the mass of the Sun, colliding 1.3 billion light-years away. In the final milliseconds of their merger, these two objects converted three entire Sun-sized masses of matter into pure gravita-



Simplified operation of a gravitational wave observatory. Figure 1: A beamsplitter (green line) splits coherent light (from the white box) into two beams which reflect off the mirrors (cyan oblongs); only one outgoing and reflected beam in each arm is shown, and separated for clarity. The reflected beams recombine and an interference pattern is detected (purple circle). Figure 2: A gravitational wave passing over the left arm (yellow) changes its length and thus the interference pattern. From figure by Cmglee, CC BY-SA 3.0.

tional energy. For that brief moment, the power output of this single event was brighter than the light of all the stars in all the galaxies in the observable universe combined.

This discovery, which earned Thorne, Weiss, and Barish the Nobel Prize in 2017, didn't just prove Einstein right; it gave humanity a new sense. We could now "hear" the universe from its earliest times. Since 2015, LIGO and its European counterpart Virgo (located near Pisa, Italy) have detected dozens of events, including the collision of neutron stars.

The neutron star merger of 2017 was particularly special. Because neutron stars are made of matter (unlike black holes), they also produced light. Astronomers around the world, using facilities like the Fermi Gamma-ray Space Telescope and the Very Large Telescope in Chile, were able to see the explosion that the gravitational waves had announced. This confirmed that the heavy elements in our universe — like the gold in your jewelry and the platinum in your electronics — are literally forged in the fire of colliding dead stars.

11.11 The Future of the "*t*-Axis"

We are now entering the era of "Multi-messenger Astronomy". Future facilities like LISA (Laser Interferometer Space Antenna) — a trio of spacecraft flying millions of miles apart — will allow us to hear even deeper, more ancient ripples

from the Big Bang itself.

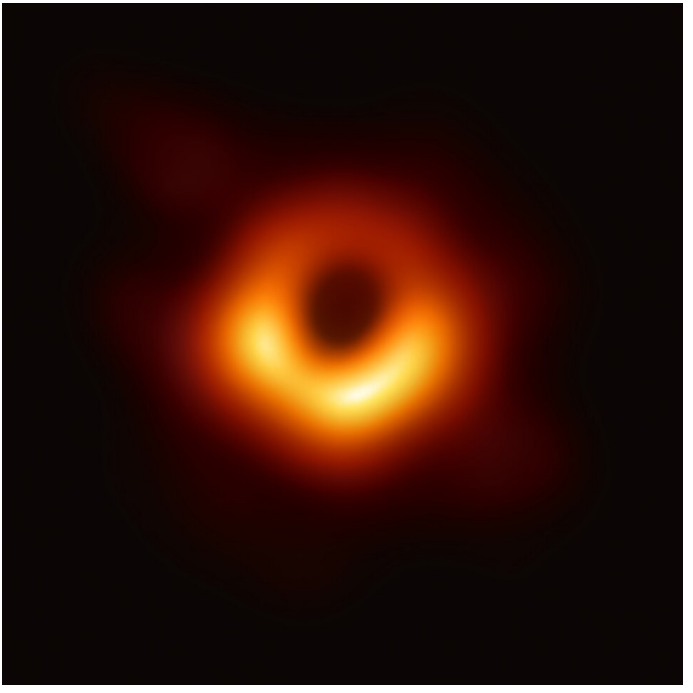
As Kozma Prutkov might have noted: "If you cannot see the truth, listen for its vibrations. Even the heaviest silence eventually breaks."

Seeing the Unseeable In the previous chapters of this book, black holes were the ultimate mathematical "Kabbalistics". They were solutions to Einstein's field equations — singularities where space and time curved so sharply that they essentially exited the universe. In 1971, the scientific community was still debating whether these "frozen stars" actually existed in reality or were merely glitches in the math. Even the author of Chapter 8 referred to "solving the equations" as the primary way of interacting with these monsters. But in the 21st century, we stopped solving and started filming.

The Earth-Sized Camera. The challenge of seeing a black hole is twofold: first, they are by definition "black" (light cannot escape them); second, they are incredibly small on the cosmic scale. Looking at the supermassive black hole in the center of our galaxy is equivalent to trying to photograph a donut on the surface of the Moon from your backyard. No single telescope on Earth had the "vision" to do it.

To solve this, a global collaboration created the Event Horizon Telescope (EHT). They used a technique called Very Long Baseline Interferometry (VLBI). By synchronizing

radio telescopes across the globe — from the Atacama Large Millimeter Array (ALMA) in Chile to the South Pole Telescope and the Submillimeter Array in Hawaii — they essentially turned the entire planet into one giant telescope dish.

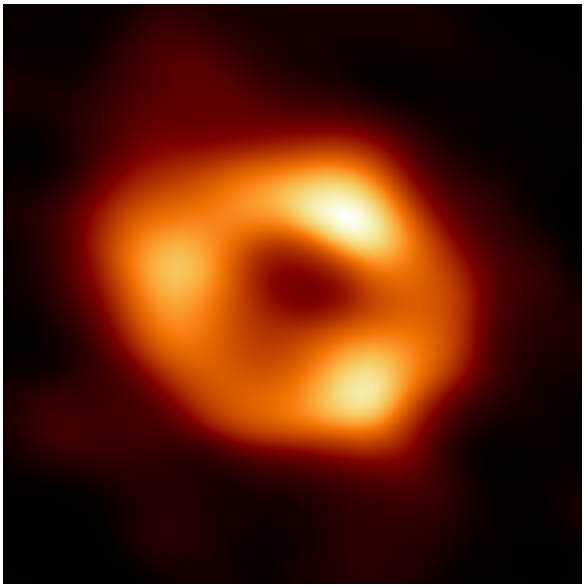


In this image of M87* taken on 11 April 2017, the shadow of a black hole is the closest we can come to an image of the black hole itself, a completely dark object from which light cannot escape. The black hole's boundary — the event horizon from which the EHT takes its name — is around 2.5 times smaller than the shadow it casts and measures just under 40 billion km across. While this may sound large, this ring is only about 40 microarcseconds across — equivalent to measuring the length of a credit card on the surface of the Moon. Credits: Event Horizon Telescope, CC BY 4.0.

M87* and the Golden Ring. In April 2019, the EHT team, led by scientists like Sheperd Doeleman and Katie Bouman

(who developed the crucial imaging algorithms), released the first-ever image of a black hole. It wasn't a photograph in the traditional sense, but a map of radio emissions from the center of the galaxy M87, 55 million light-years away.

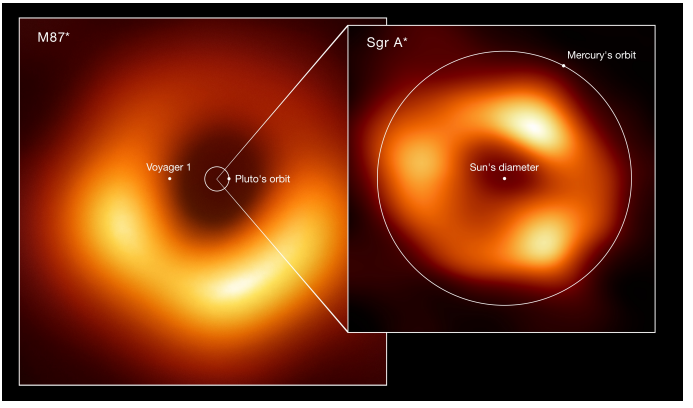
The image showed a dark central "shadow" — the event horizon — surrounded by a lopsided, glowing ring of gas and plasma being accelerated to nearly the speed of light. This was the "Accretion Disk". The asymmetry of the ring was a direct confirmation of Einstein's Special Relativity: the side moving toward us appeared brighter due to "relativistic beaming".



This is the first image of Sgr A*, the supermassive black hole at the centre of our galaxy. It's the first direct visual evidence of the presence of this black hole. Figure by EHT Collaboration, CC BY 4.0.

The Heart of the Milky Way. In 2022, the EHT did it again, this time capturing Sagittarius A*, the black hole at the center of our own Milky Way. Though it is much closer than M87, it is also much smaller and more temperamental, with the gas around it swirling so fast that the "face" of the black hole changed by the minute.

By comparing these two images, astronomers at institutions like the Max Planck Institute for Radio Astronomy confirmed that black holes are surprisingly consistent. Whether they are millions or billions of times the mass of the Sun, they follow the same geometric rules.



By EHT collaboration (acknowledgment: Lia Medeiros, xkcd) and Wikipedia link, CC BY 4.0.

The image shows the scale of Sgr A* in comparison with both M87* and other elements of the Solar System such as the orbits of Pluto and Mercury. Also displayed is the Sun's diameter and the current location of the Voyager 1 space

probe, the furthest spacecraft from Earth. M87*, which lies 55 million light-years away, is one of the largest black holes known. While Sgr A*, 27 000 light-years away, has a mass roughly four million times the Sun's mass, M87* is more than 1000 times more massive. Because of their relative distances from Earth, both black holes appear the same size in the sky.

The "shadow" we see is slightly larger than the event horizon itself because of phenomenon known as *gravitational Lensing*. The black hole's gravity is so intense that it bends the path of light, creating a "photon sphere" where light actually orbits the black hole.

The size of this shadow is determined by the Schwarzschild radius (r_s):

$$r_s = \frac{2GM}{c^2}$$

For Sgr A*, this radius is about 12 million kilometers — roughly 17 times the radius of the Sun — yet it contains the mass of 4 million Suns.

As we look at these images, we are looking at the edge of existence. Beyond that dark circle, the "wise counsel" of any thinker, including Prutkov, ceases to apply, for there is no "measurable" left — only the singularity. As Kozma Prutkov might have quipped: "If you stare into a hole long enough, do not be surprised if the hole is the only thing that stares back with perfect clarity."

11.12 The Hubble Tension: A New Crisis of Measurement

In the preceding sections, we have seen how cosmology moved from the poetic guesswork of the ancients to the "precision science" of the late 20th century. By the year 2026, we have mapped the dark matter, heard the black holes collide, and photographed the "shadow" of the abyss. We should be at the finish line. We have a "Standard Model" of the universe — the ΛCDM model — that seems to explain everything. But there is a fly in the cosmic ointment. The more precisely we measure how fast the universe is expanding, the more the universe seems to be giving us two different answers. This is the Hubble Tension.

The Two Yardsticks. To measure the expansion rate of the universe — known as the Hubble Constant (H_0) — scientists essentially use two different "yardsticks".

1. The Late Universe (*The Local Ladder*): This method, championed by Adam Riess (whom we met in the Dark Energy section) and his SH0ES team[48], uses the "Standard Candles" we discussed. By observing Cepheid variable stars and Type Ia Supernovae in nearby galaxies using the Hubble Space Telescope, they measure how fast objects are moving away from us *right now*. Their result is consistently around 73 km/s/Mpc. Cepheid variables are pulsating stars whose luminosity varies periodically; their pulsation

[48] SH0ES team — the Supernova H0 for the Equation of State programme led by Adam Riess, which measures the present-day expansion rate of the universe (the Hubble constant, H_0) using distance ladders based on Cepheids and Type Ia supernovae. – DM

period is tightly related to their intrinsic brightness (the period–luminosity relation, first established by Henrietta Swan Leavitt), making them reliable "standard candles" for measuring distances to nearby galaxies.

2. The Early Universe (*The Cosmic Blueprint*): This method uses the Planck Satellite data from the Cosmic Microwave Background. By looking at the "baby picture" of the universe from 13.8 billion years ago and using our best mathematical models to "fast-forward" to today, we can predict what the expansion rate *should* be. This result is consistently around 67 km/s/Mpc.

In the world of 1971, a difference of 6 units would have been considered a triumph of agreement. But today, with our "High-Def" tools, the error bars are so small that these two numbers no longer touch. They are in direct conflict.

The Crisis. When measurements disagree this sharply, it usually means one of two things: either someone's telescope is "lying", or our understanding of physics is incomplete. Since both teams have checked their work for a decade using different facilities — including the Gaia spacecraft for star distances and the James Webb Space Telescope (JWST) for infrared precision — the suspicion is falling on the "Mad Enough" ideas of Chapter 10.

Is there a "New Physics" we are missing? Perhaps Dark Energy isn't a constant, but changes over time. Or maybe there is a "Dark Radiation" — a fourth type of neutrino

— that sped up the early universe. Some theorists even suggest that gravity itself might behave differently on the largest scales than Einstein predicted.

James Webb Space Telescope (JWST). Launched in late 2021, the JWST, located at the L2 point alongside the ghost of WMAP, was supposed to settle the score. By peering through cosmic dust with its massive 6.5-meter gold-plated mirror, it has provided the most stable measurements of Cepheid stars in history. Yet, instead of resolving the tension, it has confirmed that the "Local" measurement of 73 is extremely solid. The gap remains. The universe is expanding faster than our best theories say it should.

As we conclude this epilogue, we find ourselves in a position that Kozma Prutkov would have found deeply ironic. We have spent billions of dollars and centuries of effort to "measure the immeasurable", only to find that the more we measure, the more the universe refuses to be tidily "arranged".

We are living through a "Crisis in Cosmology". But in science, a crisis is just a "Discovery" waiting for a better title. Whether the answer lies in a new particle, a tweak to Einstein's equations, or a fundamental misunderstanding of the "*t*-axis", the battle of ideas continues.

In the language of the Hubble Law:

$$v = H_0 \cdot D.$$

We know v (velocity) and we know D (distance), but H_0 — the heartbeat of the universe — remains a mystery that refuses to be solved by half-measures.

As our friend Kozma might say: "If you find two truths that do not agree, do not discard one; perhaps the universe is simply larger than your definition of 'agree'. "

11.13 The Next Horizon: The Engines of Discovery

If the history of cosmology has taught us anything since 1971, it is that our "mad ideas" are almost always limited by the power of our glass and the reach of our sensors. We are currently standing on the threshold of a "Golden Age of Surveying", where we stop looking at individual stars and start mapping the entire sky in high-definition motion. The next decade will be defined by three massive shifts: "Big Data" astronomy, space-based gravitational wave hunting, and the search for the first light in the universe.

Vera C. Rubin Observatory. Named in honor of the pioneer of Dark Matter, the Vera C. Rubin Observatory in Chile (nearing completion in 2026) is not a traditional telescope that looks at one thing at a time. Instead, its *Simonyi Survey Telescope* will use the world's largest digital camera (3,200 megapixels!) to photograph the entire visible sky every few nights.

This will create the Legacy Survey of Space and Time (LSST) — essentially a 10-year "movie" of the cosmos. It will track billions of galaxies, monitor how they cluster, and observe how Dark Energy pushes them apart in real-time. By seeing how the "web" of the universe changes over a decade, we may finally see if Dark Energy is a constant or if it evolves.

The Roman and Euclid Era. While the James Webb Space Telescope (JWST) is a "sharpshooter" that looks deep and narrow, two new missions are designed to look "wide".

ESA's Euclid Mission: Already in orbit, Euclid is creating a 3D map of the universe by looking back 10 billion years. Its goal is to measure the "shape" of the dark universe by observing how gravity warps the light of distant galaxies (weak lensing).

NASA's Nancy Grace Roman Space Telescope: Set to launch soon, Roman will have a field of view 100 times greater than Hubble. It is specifically designed to hunt for Dark Energy and exoplanets, potentially finding thousands of new worlds and "standard candle" supernovae.

Listening to Gravity. While LIGO allowed us to "hear" the high-pitched chirps of small black holes, the Laser Interferometer Space Antenna (LISA) will allow us to hear the deep, low-frequency "bass" of the universe. Led by the European Space Agency (ESA) and NASA, LISA will consist of three spacecraft flying in a triangular formation, 2.5 million

kilometers apart, trailing the Earth in its orbit around the Sun.

Recent breakthroughs using Pulsar Timing Arrays (like NANOGrav) have hinted that the entire universe is "humming" with a background sea of gravitational waves. By using rapidly spinning dead stars (pulsars) as a galaxy-sized clock, institutions like the National Radio Astronomy Observatory (NRAO) are trying to detect the slow, rolling waves caused by the collective motion of all the supermassive black holes in existence.

The expansion of the LIGO-class detectors into a truly global network — spearheaded by the upgrades to the American sites and the construction of LIGO-India (IndIGO) near Aundha, Maharashtra — addresses the critical problem of "sky localization" in multi-messenger astronomy. Currently, with only a few detectors, pinpointing the exact origin of a spacetime "ripple" is like trying to find a needle in a cosmic haystack; the addition of the Indian detector provides the necessary "baseline" to triangulate sources with unprecedented precision. This network will solve the Hubble Tension by using "standard sirens" (binary neutron star mergers) to measure the universe's expansion rate independently of traditional telescopes, while also allowing us to "hear" the internal dynamics of black holes and supernovae that remain invisible to light-based instruments.

The Square Kilometre Array (SKA). On the ground, the Square Kilometre Array (SKA) — located across sites in South Africa and Australia — will be the largest and most sensitive radio telescope ever built. It will allow us to map the distribution of hydrogen gas before the first stars were even born, essentially filling in the "missing chapters" between the Big Bang and the modern universe.

Simons Observatory and CMB-S4. The Simons Observatory and the upcoming CMB-S4 project are designed to solve the mystery of the universe's first fraction of a second by searching for "B-mode polarization" — faint swirls in the Cosmic Microwave Background that would act as a "smoking gun" for Cosmic Inflation. While previous missions like Planck gave us a high-resolution "baby picture" of the universe, these next-generation experiments will look deeper into the noise to determine the mass of neutrinos and the nature of the "Dark Energy" that began dominating cosmic expansion billions of years later. By combining ground-based data from the high-altitude deserts of Chile and the pristine atmosphere of Antarctica, they aim to turn the theoretical "Inflation" phase from a compelling idea into an observed fact.

Large-Scale Structure: DESI and the Dark Energy Puzzle. The Dark Energy Spectroscopic Instrument (DESI) addresses the "Dark Energy" problem by creating the largest 3D map of the universe ever attempted, charting tens of millions of

galaxies and quasars across 11 billion years of cosmic history. By measuring Baryon Acoustic Oscillations (BAO)—the "frozen sound waves" from the early universe—DESI can track how the expansion of space has accelerated over time with 1% precision. This will solve the fundamental question of whether Dark Energy is a "Cosmological Constant" (an unchanging energy of empty space) or a dynamic field that evolves, potentially revealing whether our universe will eventually end in a "Big Freeze" or a "Big Rip".

11.14 The Mathematical Horizon

As we build these machines, the theorists are not sitting idle. The next great "mad idea" may come from Quantum Gravity or String Theory, attempting to unite the "Kabbalistics" of the subatomic world with the "Magnificent Theorems" of Riemann and Einstein.

The goal is a single equation that explains the "Dark Side" of the cosmos.

A Final Prutkovian Outlook on the Future: "Do not fear the coming dawn, for though it reveals how much we have yet to learn, it also proves that the light is still winning. The telescope of tomorrow is merely the eye of today, opened a little wider."

11.15 Concluding Thoughts

The Unfinished Symphony of the Cosmos. As we close this journey — a journey that began with the rigid, eternal lines of Euclid and ends in a universe that is accelerating, invisible, and perhaps even "mad" — we find ourselves at a strange and beautiful vantage point.

When this book was written in 1971, the universe felt like a puzzle with only a few missing pieces. We thought we knew the "matter" of the world; we just needed to measure its expansion a bit more precisely. But as we have seen in these ten chapters and our modern epilogue, the act of "measuring the immeasurable" has revealed not just a larger room, but an entirely different house.

From the "Magnificent Theorem" of Gauss to the warped space-time of Einstein, the central theme of this book has been that Geometry is Destiny. The shapes we once thought were abstract exercises in a Greek classroom have become the literal architecture of reality. The "Dark Side of the Cosmos" is not a failure of our math; it is a testament to its power. We discovered Dark Matter and Dark Energy not because we saw them, but because the geometry of the universe demanded they exist.

The "Kabbalistics" of the twentieth century have matured into the "Precision Cosmology" of the twenty-first. We have moved from solving equations on a chalkboard to hearing the collision of black holes from across the void. We have realized that we are made of the 5% "visible" foam

on a vast, dark ocean. If the ideas in Chapter 10 seemed "not mad enough" in 1971, today's reality — where space-time ripples like a pond and the vacuum of space has a "price tag" of energy — would have seemed like pure sorcery to the ancients.

Kozma Prutkov, our guiding wit throughout this exploration, famously remarked: "One cannot embrace the unembraceable." And yet, that is exactly what humanity has attempted to do. We have looked at the "*t*-axis"", mapped the "Great Explosion", and stared into the "Shadows of the Abyss".

The universe remains a work in progress. The Hubble Tension and the mysteries of Quantum Gravity remind us that the book of nature is never truly finished; we are merely starting a new volume.

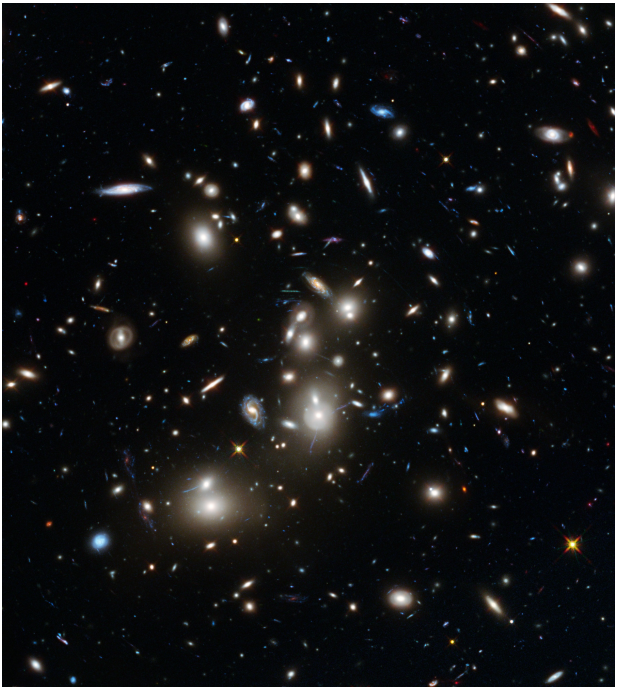
The math of the future will likely be as different from Einstein's as his was from Euclid's. But the goal remains the same: to find the "Harmony of the Universe" in the midst of the dark.

Total Reality = The Seen + The Unseen + The Yet To Be Imagined

A final quip from our friend Kozma:

> "If you reach the end of your map and find the world continues, do not be afraid. It simply means you have been given the privilege of drawing the next line."

Till then, I leave you with another amazing image of the cosmos.



Hubble Frontier Fields view of Abell 2744. This image of Abell 2744 is the first to come from Hubble's Frontier Fields observing programme, which is using the magnifying power of enormous galaxy clusters to peer deep into the distant Universe. Abell 2744, nicknamed Pandora's Cluster, is thought to have a very violent history, having formed from a cosmic pile-up of multiple galaxy clusters. Image By NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI). Public Domain, via Wikimedia.

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